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Part II

THE EXTRUSION, FORGING, ROLLING, AND EVALUATION OF REFRACTORY ALLOYS

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NOTICES

FOREWORD

This report was prepared by Westinghouse Electric Corporation under USAF Contract Number AF 33(616)-8325. This contract was administered under the direction of the Research and Technology Division, Air Force Materials Laboratory, with Mr. V. DePierre as Air Force Project Engineer.

The program was conducted under the technical direction of D. R. Carnahan, Lead Engineer, with G. A. Reimann and J. A. Visconti as Project Engineers. Significant contributions have been made to this program by Messrs. V. DePierre and M. M. Myers of AFML, and R. A. Sweeney and T. E. Jones of Westinghouse. The authors are indebted to 1st. Lt. C. M. Pierce of AFML for his assistance in preparing the theoretical discussion.

This report covers work conducted from 1 August, 1962 to 31 May, 1963.

ABSTRACT

Wrought bars of tungsten-base alloys were produced by extrusion of arc-cast billets under a variety of conditions. Billets of W+0.6Cb alloy were successfully extruded using temperatures between 3200 and 4200°F and reduction ratios between 3.9:1 and 8.3:1. A comparison was drawn between W+0.6Cb extrusions produced from material melted by four suppliers. Differences in material characteristics could be traced to electrode suppliers.

The W+6Mo+2Cb alloy was extruded between 3400 and 4200°F using ratios from 4.1:1 to 7.4:1. Surfaces were generally fair to poor and internal cracks were discovered in many extrusions. Machining billets from 4-inch ingots instead of 3½-inch ingots produced only a slight improvement in extrusion quality.

Instrumentation of the extrusion press to measure ram load, die load, and ram position has enabled a realistic determination of container friction and a modification of basic extrusion theory.

Jacketing tungsten-base billets with molybdenum was found more advantageous than applying glass as a lubricant, particularly at elevated temperatures.

While swaging has been the most successful method for reduction of tungsten-base extrusions, higher tensile properties were obtained at 3000°F on forged material (46,200 vs. 63,300 psi for W+0.6Cb). An ultimate strength of 48,200 psi was obtained on swaged W+6Mo+2Cb alloy.

This technical documentary report has been reviewed and is approved.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES
(continued)

LIST OF FIGURES

(continued)

I. INTRODUCTION

The objectives of this investigation were to develop new processes and techniques for the extrusion, forging, rolling, and swaging of refractory alloys, including a metallurgical evaluation of the material during each stage of the processing cycle. This investigation is a continuation of and a supplement to the work previously reported in ASD-TDR-62-670(1).

The tungsten + 0.6 percent columbium and the tungsten + 6 percent molybdenum + 2 percent columbium compositions were selected as the subject alloys for this investigation. The tungsten + 0.6 columbium alloy was developed by the Union Carbide Metals Company and a tensile strength of 60,600 psi at 3000°F in vacuum was reported in WADD-TR-60-144(2), indicating that this binary composition was considerably stronger than unalloyed tungsten or other tungsten-base alloys containing minor additions. A number of investigators have developed reliable arc melting techniques for producing sound ingots of the W+0.6Cb composition. A successful vacuum arc melting process is described in detail in ASD-TDR-63-296(3). Ten W+0.6Cb billets were chosen to supplement extrusion information reported in ASD-TDR-62-670.

The 92% tungsten + 6% molybdenum + 2% columbium composition, hereafter abbreviated as 92-6-2, was modified from the original 88W+6Mo+6Cb alloy developed by the Crucible Steel Company(4). The 88-6-6 alloy exhibited a tensile strength of 62,000 psi at 3000°F in vacuum. Crucible's 88-6-6 ingots were made in 1¼-inch segmented molybdenum molds by melting multiple wire electrodes with alternating current. Severe ingot cracking was encountered while developing melting parameters to produce the 88-6-6 alloy in 3½-inch water cooled copper molds with direct current. The columbium content was reduced from 6 to 2 percent so that crack-free 3½-inch diameter ingots could be produced(5). The 92-6-2 alloy was chosen for this investigation to compare its extrudability with W+0.6Cb.

II. PROGRAM

The program consisted of four work areas which were accomplished concurrently. The work areas were: (a) basic extrusion study, (b) thermal-mechanical effects study, (c) maximum yield effort, and (d) Air Force Materials Laboratory internal program support. These are described as follows:

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(a) A basic study of extrusion variables to determine optimum conditions for the extrusion of refractory alloys constitutes one of the major areas. The particular alloys in this study were W+0.6Cb and 92W+6Mo+2Cb.

(b) The thermal-mechanical effects area consisted primarily of establishing the forging, rolling and swaging aspects of the program and the major portion of the metallurgical testing, evaluation, and analysis.

(c) Extrusion work scheduled in conjunction with Air Force, Navy, and other governmental agency contractors directed toward obtaining the maximum yield from experimental alloys.

(d) Internal program support consisted of processing a variety of experimental material and providing services to support internal programs in the Air Force Materials Laboratory.

A program outline describing the work conducted under work areas (a) and (b) is as follows:

A. <u>Basic Extrusion Study</u>

1. <u>W+0.6Cb (seven arc cast billets)</u>

a. Sectioned one billet to examine macrostructure.

b. Extruded six billets to rounds at 3800 and 4000°F.

c. Evaluated extrusions.

(1) Surface, soundness, dimensions
(2) Weight percent yield
(3) Hardness, microstructure, and recrystallization behavior at nose, center and tail

2. <u>92W+6Mo+2Cb (thirty arc cast billets)</u>

a. Sectioned one billet to examine macrostructure.

b. Extruded eight billets to study extrusion parameters.

c. Extruded twelve billets to rounds at 3800, 4000 and 4200°F to provide material for workability evaluation.

d. Extruded nine billets to rectangles at 3800, 4000, and 4200°F to provide material for workability evaluation.

e. Evaluated extrusions.

(1) Surface, soundness, dimensions
(2) Weight percent yield
(3) Hardness, microstructure, and recrystallization behavior at nose, center, and tail
(4) 3000°F vacuum tensile tests

B. Thermal-Mechanical Effects Study

The following refers to both the W+0.6Cb and the 92-6-2 alloys.

1. Forging

a. Forged annealed samples to establish minimum permissible forging temperature.

b. Forged annealed samples at three temperatures and four reductions to evaluate material.

c. Evaluated forgings.

(1) Hardness and soundness
(2) Recrystallization behavior

2. Rolling

a. Rolled annealed forgings at three temperatures and four reductions.

b. Evaluated rolled material.

3. Swaging

a. Swaged round extrusions at three temperatures and four reductions.

b. Evaluated swage stock.

(1) Surface, soundness, dimensions
(2) 3000°F vacuum tensile tests

III. THEORETICAL CONSIDERATIONS[6]

Figure 1 is a schematic illustration of an extrusion process. Referring to this figure, the general force equation in the x-direction is expressed as

$$F_t = F_{ff} + F_{fb} + F_d \qquad (1)$$

where

F_t = total force required to sustain extrusion

F_{ff} = frictional force between the container and the follower material

F_{fb} = frictional force between the container and the upset billet (a function of the normal force, N)

F_d = force applied on the die (deformation force + die friction)

Prior to this time fabricators have measured only the total force, and material extrudability has been related to an extrusion constant (K-factor) which is given by:

$$K = \frac{F_t}{A_o \ln \frac{A_o}{A_x}} \qquad (2)$$

where

A_o = cross-sectional area of the upset billet

A_x = cross-sectional area of the extruded product

It is generally assumed that the lower the extrusion constant, the more easily deformed is a material during the extrusion operation.

It was determined from recent tests on 1018 steel extrusion billets that the force required to overcome container friction varied from extrusion to extrusion and was markedly influenced by the type of applied lubricant, the condition of the container liner, and the billet temperature[7]. Some of the scatter in extrusion constant data encountered throughout industry is caused by these variations.

Unique instrumentation (discussed in Section IV) of the extrusion press at the Air Force Materials Laboratory has made it

possible to measure directly the force on the die and the change of billet length in the container in addition to the total force required for extrusion. Die force data provide more meaningful determinations of material deformability because they are unaffected by container friction.

Typical data traces, showing total force on the ram, F_t, the force on the die, F_d, and ram displacement are displayed schematically in Figure 2. Were billet friction the only cause for the difference between the total force and the die force, the extrapolated F_t would intersect F_d where billet friction was zero, or at a point corresponding to zero billet length. Considerable displacement is observed at this point which is attributed to friction between the follower material and the container. The total force on the billet must be expressed now as $F_t - F_{ff}$. The friction force, F_{ff}, which was indeterminable before die load data were available, is assumed to be constant during the extrusion stroke when the coefficient of friction between the billet and the container is calculated.

At any instant, i, the force required to sustain extrusion of a billet is given by[8]:

$$F_i = F_o e^{\left(\frac{4u}{D}L_i\right)} \qquad (3)$$

where:

F_i = total force exerted on the billet

F_o = deformation force exerted on the billet

D = diameter of the upset billet

u = coefficient of friction between billet and container liner

L_i = length of upset billet

Previously, investigators determined the total force curve only, proceeded to let F_i in equation 3 equal the measured F_{ti}, and assumed that the deformation force, F_o, was equal to the measured $F_t$min. It has been pointed out that the actual force on the billet is $F_t - F_{ff}$, and the deformation force, F_o, is equal to the force measured behind the die, F_d.

To calculate the coefficient of billet friction, u, the total force (as expressed by equation 3) at two points during extrusion are subtracted from one another, and the resulting equation is:

$$F_{t_1} - F_{t_2} = F_d\left[e^{\left(\frac{4u}{D}L_1\right)} - e^{\left(\frac{4u}{D}L_2\right)}\right] \qquad (4)$$

The coefficient, u, can be calculated from this expression. Inasmuch as u is influenced by departure of the billet from ideally plastic behavior, billet temperature, and the effect of the composition of the layer between billet and container liner, the values of u should be considered "effective" coefficients of friction.

IV. EXPERIMENTAL PROCEDURE

The details of the basic extrusion process and general AFML practices relating to subsequent metalworking operations used in this investigation have been described in ASD-TDR-62-670. Equipment added or modified and any procedural changes made during the contractual period are discussed in the following section.

A. Extrusion

A Minneapolis-Honeywell Model 1508 Visicorder (Figure 3) was installed at the extrusion press in place of the 906B model, a smaller and somewhat less versatile instrument. The new recorder uses a wider chart and presently employs nine active data channels, although up to 24 channels are available if desired. The nine channels provide data on ram load, die load, ram position, ram speed, extrusion temperature, and the load on each of the four tie rods. Tie rod tension is recorded during extrusion as a means of measuring the uniformity of loading and to detect if the bolster becomes misaligned.

Ram load is measured with a pressure transducer attached to the hydraulic system. Ram speed is measured by a tachometer coupled to a drum which is rotated by a cable fastened to the ram. The cable is under spring tension to eliminate slippage and backlash. A 10-turn variable potentiometer is attached to the drum shaft opposite the tachometer and produces a voltage which varies linearly with the ram position.

The die load measurements are obtained from a load cell positioned directly behind the die by modified backup tooling, shown in Figure 4. This modification does not significantly alter the extrusion procedure, although strain gages must be protected from overheating and calibration of the load cell must be checked occasionally to insure that false readings are not obtained because of plastic deformation of the cell under high die loadings.

The first set of tooling for die force measurements was designed to accommodate a nominal 1.25-inch diameter (6:1) extrusion. A .125-inch clearance was considered

adequate to minimize the possibility of interference between the extrusion and the load cell due to nose bursts or other extrusion deformities. This required a 1.5-inch bore in the load cell, placing it somewhat at a disadvantage with respect to cross-section. The stem of the press will withstand at least 700 tons without plastic deformation, but to allow passage of the extrusion, the load cell cross-section is reduced nearly 25 percent and the maximum load to about 530 tons. Increasing the bore diameter to accommodate larger extrusions further reduces allowable tonnage. The calibration step, where a room temperature steel billet is pressed against a die and the stem and die loads are matched against a hydraulic gage, endangers the load cell because the full press tonnage is transmitted directly and can be reached very quickly. Fortunately, in practice, die loads have not exceeded 400 tons even though stem loading is considerably higher because of container friction.

An instrument for sensing the temperature of the emerging extrusion was purchased and is being tested. The device was manufactured by Radiation Electronics Company and is sold under the tradename "Thermodot". It focuses infrared energy emitted by an object onto a lead sulphide detector which generates a signal that is amplified and recorded on the Visicorder. The backup tooling was modified to allow sensing of the extrusion temperature, and both the die load and temperature of the extrusion can be measured simultaneously.

B. <u>Forging</u>

The inert atmosphere forging chamber was removed from the forge press. Mechanical difficulties and operational encumberances were such that neither time nor funds would allow the experimentation and modification considered necessary for the chamber to be operated effectively. Difficulties included fracture of the ¾-inch clear plastic chamber top by a combination of tightly-fitting seals and minor die misalignment. The cracked top was patched and the o-ring seal around the die was replaced by plastic bellows.

A large quantity of argon was required to effect an adequate exchange of atmosphere inside the chamber and a steady flow of argon was required to maintain sufficient positive pressure to preclude entry of air during forging. Fluctuating argon temperatures and changes in chamber volume accompanying press movement made it difficult to insure adequate positive pressure of argon. A small quantity of air in the chamber would result in oxidation of the tungsten susceptor and the hot specimens, and the reliability of optical temperature control would be reduced by the fumes.

The induction furnace would heat tungsten and molybdenum specimens to 3200°F without difficulty, and specimens could be forged without surface discoloration when the chamber was adequately purged. No suitable means was found to slowly cool samples of alloys sensitive to thermal shock.

Since relatively few tungsten or molybdenum base samples comprised a single forging experiment, argon consumption on a per-sample basis was very high. Also, surface condition and as-forged dimensions as influenced by oxidation were secondary to alloy deformability and internal soundness. The latter characteristics can be determined readily by heating in an argon atmosphere resistance furnace and forging in air.

The Minneapolis Honeywell Model 906B Visicorder, which was used to measure extrusion variables prior to its replacement by the 1508 model, was moved to the forge press so that pressing speed, ram displacement, and deformation pressure can be recorded.

C. Swaging

A Fenn Model 6F, 2-die rotary swaging machine (Figure 5) was purchased during the contractual period. Swaging dies from 1.188 to .375-inch diameter are in use at this time.

V. DISCUSSION AND RESULTS, BASIC EXTRUSION STUDY

A. W+0.6Cb Billets

Ten billets of W+0.6Cb alloy were requisitioned to fulfill the requirements of the basic extrusion study. Eight billets were ordered from the Wah Chang Corporation and two billets were obtained from the Oregon Metallurgical Corporation to provide an opportunity to compare billets provided by these two suppliers to the material produced at AFML and Universal Cyclops which was extruded previously.

The seven billets received from the two suppliers ranged from 2.941 to 2.950 inches in diameter, 4.313 to 4.750 inches in length, and between 20.3 and 22.3 pounds. A ¼-inch x 45° chamfer was machined into the top (lead) end of each billet to aid in the initiation of extrusion and to minimize die damage. Billet hardness averaged 65 Rockwell A. The suppliers' ultrasonic and zyglo

examinations indicated that all billets were sound and visual examination of billet surfaces did not disclose any other defects. A comparison of billet structure could not be made because the five Wah Chang billets had been extruded before it was learned that the order was not to be completed, and no Wah Chang material was sectioned for macro-examination. One of the Oremet billets was cut longitudinally and the macrostructure is shown in Figure 6 with a macrosection of a W+0.6Cb ingot produced at AFML shown for comparison.

The analytical data for the W+0.6Cb billets are shown in Table 1. These data indicate that the W+0.6Cb billets supplied by Wah Chang and Oremet are very similar in chemistry to the majority of other W+0.6Cb billets extruded at the AFML facility, however, three of the billets supplied by Wah Chang contained roughly twice as much columbium as the other billets.

B. Extrusion of the W+0.6Cb Alloy

The six W+0.6Cb billets extruded as part of this program were coated with Corning #7900 glass, heated to either 3800 or 4000°F, and extruded using ratios between 4.3:1 and 7.3:1. All the billets were successfully extruded and the data are summarized in Table 2. The Wah Chang billets used to produce extrusions 994, 995, and 996 contained more columbium than the rest, as mentioned in the previous paragraph, but doubling the columbium content at these concentrations apparently has little effect on extrudability.

A number of other W+0.6Cb billets were extruded at AFML and comparisons of material characteristics may be drawn by examining data from billets produced by Universal Cyclops for Part I of this investigation, and from material produced in the AFML arc furnace for a separate arc melting study(3). Extrusion data for these billets are listed in Table 2 and comparative analytical data are shown in Tables 1 and 3.

Figures 7 and 8 show the K factor values obtained from the W+0.6Cb billets listed in Table 2. Considerable data scatter (the causes of which were discussed in Section III) is evident; and, for this reason, a K factor band is shown instead of a line.

Several total stem load and die load traces are shown in Figure 9. Only total load traces are available for extrusions 992, 993, and 994, but both total load and die load curves are shown for extrusions 995, 996, 997

and 1050. Traces have been superimposed for ease of comparison.

The total load decreases in each case after the billet begins to extrude because of decreasing frictional effect as billet length decreases, although the load always increases again after extrusion is more than 60 percent complete because of billet heat loss and the diminishing effectiveness of the high temperature lubricant. This increase is not reflected as sharply at the die. The degree or effect of material heating during deformation in the die is not known.

In Figure 9 it will be observed that total load for extrusion 1050 decreases while die load increases. Since all billets were coated with Corning 7900 glass except for the one from which extrusion 1050 was produced, the increasing die load in this instance is believed to result from greater billet heat loss due to the absence of the glass coating. This provides an indication of the insulating properties of the coating.

The die load data obtained on the four W+0.6Cb alloy billets extruded during this program are shown below. The die K factor figures were obtained by inserting the maximum (breakthrough) tonnage values on the die into the equatio . Corresponding stem load data were extracted from Table 2 for comparison.

			STEM DATA			DIE DATA		
Extrusion Number	Temp (°F)	Ratio	Max Tons	Min Tons	K (psi)	Max Tons	Min Tons	K (psi)
995 (WC)	3800	6.6:1	450	410	64,300	370	360	53,000
996 (WC)	4000	6.4:1	500	430	72,500	360	335	52,200
997 (OM)	3800	6.5:1	560	480	80,800	340	305	49,100
1050 (UC)	3800	6.2:1	500	460	74,000	390	370	56,400

The K factor values obtained at the die were plotted in Figure 9 on the same scale used for plotting K factors in Figures 7 and 8. While the conclusions that might be drawn are limited because die load data were obtained on only four billets, the above tabulation indicates that little correlation exists between the K factor measured at the stem and the one measured at the die. Based on total load measurements, the Oremet billet was the most difficult to extrude, followed in order by extrusion 1050, 996, and 995. Die load measurements indicate that the Oremet billet was the least difficult to deform, followed in increasing order by extrusions 996, 995, and 1050. As discussed in Section III, the die measurements are considered a more reliable indicator of billet deformability.

The frictional force on the follower material has already been discussed (see Section III) and tends to increase the stem load above the load required to actually deform the material. During extrusion of the Oremet billet, it was noticed that a portion of the zirconia pedestal block, upon which the billet rests during heating, had adhered to the base of the billet. In addition to the force required to extrude the alloy, considerable force was needed to overcome friction between the abrasive zirconia and the container liner. This condition contributed to the high stem load recorded for this extrusion.

If the die K factors plotted in Figure 9 present an accurate indication of the effect of temperature on deformability, the slope of the line shows that changing billet temperature has a less pronounced effect on die K factor than on the stem extrusion constant. The degree of data scatter at the die is not evident, considering the conditions of extrusion and the number of measurements.

The coefficient of friction between the billet and the container was calculated by use of equation 4(Page 5). The results of these calculations are as follows:

Extrusion Number	Coefficient of Billet Friction
995	0.050
996	0.070
997	0.085
1050	0.045

Analytical data in Tables 1 and 3 indicate that the W+0.6Cb billets supplied by Wah Chang contained a higher interstitial and residual metallic impurity level than billets supplied by Universal Cyclops and AFML. However, the results of deforming operations are not in agreement with the apparent differences in purity levels. The extrusion data show that the Wah Chang material was more easily extruded and photomicrographs (Figures 10 and 11) show that the alloy showed a stronger tendency to recrystallize during the process, both signs suggesting a higher purity material. This tendency also was noted when extruding a W+0.6Cb billet produced in the AFML furnace from Wah Chang electrodes (Ingot VA-86, Extrusion 956).

The apparent lack of correlation between billet chemistry and extrudability does not indicate analytical error, but rather it reflects a difference in analytical and reporting techniques, with a predominance of higher "less than" values reported by Wah Chang

implying higher impurity levels. Ingot VA-86 was produced in the AFML furnace from the same electrode lot utilized by Wah Chang for their ingots. The analysis of this ingot by Le Doux, Inc., shown in Table 3, indicates very little difference in chemistry exists between this and other ingots shown in the table except for carbon and oxygen. While the "less than" values reported by Wah Chang are undoubtedly correct, the actual values appear considerably lower than many of those indicated. Differences in extrudability and other properties may be related to electrode suppliers as well as to differences in arc melting technique.

Data have been extracted from Tables 1, 2, and 3 and arranged to show the relation of carbon content to K factor. All of the billets listed below were heated to 3800°F for extrusion.

Extrusion Number	Billet No. & Source	Electrode Source[a]	Extrusion Ratio	Reported ppm C	K Factor (psi)
752	KC1138A(UC)	GE	4.1:1	44	80,500
753	KC1138B(UC)	GE	7.6:1	44	82,500
755	KC1146A(UC)	Sy	4.4:1[b]	45	87,500
756	KC1146B(UC)	Sy	5.5:1[b]	45	84,400
757	KC1137A(UC)	GE	6.7:1[b]	27	87,400
762	KC1145B(UC)	Sy	4.2:1	50	90,800
1050	KC1148B(UC)	Sy	6.2:1[c]	43	74,000
896	VA-68(AFML)	GE	6.3:1	44	Stuck
935	VA-78(AFML)	GE	6.4:1	10	75,000
936	VA-79(AFML)	GE	8.4:1	18	75,000
948	VA-83U(AFML)	GE	6.4:1	123	Stuck
951	VA-83L(AFML)	GE	3.0:1	123	Stuck[d]
956	VA-86(AFML)	WC	6.4:1	6	72,700
957	VA-87(AFML)	W	6.4:1	51	Stuck
958	VA-88(AFML)	GE	6.4:1	230	Stuck
966	VA-91(AFML)	GE	6.4:1	230	Stuck
974	VA-92(AFML)	W	6.3:1	25	83,800
992	31015T(WC)	WC	4.3:1	30	76,000
995	31192B(WC)	WC	6.6:1	30	64,300

(a) Sources: UC - Universal Cyclops, GE - General Electric, Sy - Sylvania, AFML - Air Force Materials Laboratory, W - Westinghouse, WC - Wah Chang

(b) Rectangular Die

(c) No glass lubricant

(d) Billet heated to 4200°F

More data on the effect of carbon can be determined by converting 4000°F K factor data to 3800°F data. This was done by adding 6,000 psi to the 4000°F K factor values, which would be the expected increase according to the slope of the K factor band.

Extr. No.	Billet No. & Source	Electrode Source	Extr. Ratio	Reported ppm C	Converted K Factor (psi)
632	KC1072(UC)	Sy	4.4:1	21	95,400
746	KC1143A(UC)	Sy	4.0:1	20	80,700
747	KC1143B(UC)	Sy	7.9:1	20	82,000
758	KC1147A(UC)	GE	4.5:1(b)	60	77,800
759	KC1147B(UC)	GE	7.0:1(b)	60	88,000
763	KC1145A(UC)	Sy	4.1:1	50	79,400

(Notes of previous tabulation apply)

The addition of carbon alone to the W+0.6Cb alloy could be beneficial if increases in elevated temperature strength can be obtained while still having an extrudable alloy. A "go - no go" diagram is shown in Figure 12, where successful and unsuccessful extrusions are plotted according to carbon content and extrusion ratio. It appears that 40 to 60 ppm carbon is the critical range where the W+0.6Cb alloy becomes so resistant to deformation that it cannot be extruded by present Air Force Materials Laboratory extrusion techniques and equipment.

C. Evaluation of W+0.6Cb Extrusions

The surface condition of extrusions were rated according to the examples shown in Figure 13. Surface condition was determined after oxide, glass lubricant and adhering Sil-O-Cel had been sandblasted away. The surfaces of the W+0.6Cb extrusions were generally good, regardless of the supplier. Defects that did exist were of such a nature that frequently one was able to identify the source of the billet from the nature of the extrusion surface. An ingot melted in the AFML

furnace from Wah Chang electrodes produced an extrusion surface similar to that found on extrusions produced from material melted by Wah Chang. AFML and Universal Cyclops ingots melted from General Electric electrodes produced extrusions which had similar surfaces. Examples of extrusion surfaces are shown in Figure 14.

Except for obvious laps, seams, and fissures, little could be said about the exterior layer of the extruded material. It was found that many defects were hidden by smeared metal and were not detected until sampleswere severely etched or subjected to deformation perpendicular to extrusion direction. Machining 60 to 100 mils from the surface removes all but the most serious defects. It is believed that greater material recovery could be obtained by improving billet machining methods to avoid generating minor surface cracks that tend to propagate during billet extrusion. The surface of extrusion 1050, which was produced from an uncoated billet, was found to be at least as good as if not better than the surfaces of extrusions produced from glass-coated billets.

The dimensions of the W+0.6Cb extrusions generally increased from nose to tail because of die wear. Dimensional variation, in inches, of extrusions produced from Wah Chang billets and from several Universal Cyclops billets are shown below.

Ext. No.	Temp. °F	Nose	Center	Tail
992 (WC)	3800	1.482	1.483	1.483
993 (WC)	4000	1.482	1.479	1.482
994 (WC)	4000	1.135	1.130	1.140
995 (WC)	3800	1.193	1.197	1.208
996 (WC)	4000	1.215	1.210	1.214
752 (UC)	3800	1.518	1.520	1.523
753 (UC)	3800	1.116	1.118	1.120
743 (UC)	4000	1.225	1.228	1.230
744 (UC)	4000	1.141	1.144	1.156
935 (AFML)	3800	1.203	1.208	1.208
936 (AFML)	3800	1.063	1.065	1.074
956 (AFML)	3800	1.214	1.215	1.216

From the data it is apparent that the effect of the W+0.6Cb alloy on the dies is about the same, regardless of billet source.

Extrusions were sampled according to the diagram in Figure 15 unless special sampling was required for a separate study.

Nose, center, and tail samples of W+0.6Cb extrusions produced from billets supplied by four different arc melting facilities are shown in Figure 16. These structures resulted from extruding at 3800°F through round dies giving approximately a 6.5:1 reduction ratio. In all cases the center sample shows more recrystallization than either the nose or tail samples. This observation is supported by the hardness data which is presented in Table 4. The nose and tail sections were harder than the center section. The structure contained in the center sample is considered representative of that contained in about 75 percent of the bar. The nose region of the bar suffers heat loss during transfer and from contact with the relatively cold nose plug in addition to being subjected to less deformation. The tail region suffers greater heat loss because of the length of time for contact with the cold container and the proximity of the graphite follower block which is normally at room temperature when placed in the container.

D. 92W+6Mo+2Cb Billets

Thirty billets of the 92-6-2 composition were to be obtained from two outside suppliers, so Oremet and Wah Chang were contacted and requested to quote on 15 billets each. Because of the tendency of arc melted ingots of this alloy to crack, both of the mentioned suppliers declined to quote on this order and it was necessary to produce all of the ingots in the AFML furnace.

Electrode material for these ingots was obtained from the General Electric Corporation as 1½-inch diameter, hydrostatically pressed and hydrogen sintered bars of a 94 percent tungsten + 6 percent molybdenum mixture. Each electrode contained a 3/8-inch bore through which wires of columbium were inserted to provide the 2 percent addition. All electrodes were joined mechanically with a 1-8NC thread. The characteristics of the material, as provided by the supplier, are shown in Table 5.

The ingots were produced without difficulty using parameters similar to those developed during the investigation of arc melting this alloy(5). A typical melting record for the production of 3½-inch ingots is shown in Table 6. The melting current was increased slightly, from 5500 to 5800 amperes, in an effort to obtain better ingot surfaces. An arc cast ingot and a machined billet are shown in Figure 17 and the ingot macrostructure is displayed in Figure 18. The ingot grain size is considerably finer than the grain size of the W+0.6Cb ingots shown in Figure 4, a result of the 6 percent molybdenum addition and the increased columbium content. Some ingot microstructures are shown in Figure 19. These structures are typical of tungsten base alloys and do not show any second

phase at the grain boundaries although a fairly large number of voids are evident at low magnification, where inclusions were removed during electropolishing and etching.

Although all billets were machined to a nominal 2.940-inch diameter, lengths ranged between 3.5 to 6.6 inches, and weights varied between 15.6 and 18.5 pounds. No ultrasonic facilities were available at AFML for detection of internal billet flaws, so as an alternate, visual inspection was used to detect flaws that extended to the billet surface. Billet hardness data are shown in Table 7 and billet analyses are shown in Table 8.

E. Extrusion and Evaluation of the 92W+6Mo+2Cb Alloy

Extrusion data for 92-6-2 billets are summarized in Table 9. Generally the pressure required to extrude the 92-6-2 billets exceeded that needed to extrude the W+0.6Cb alloy at the same temperatures and reductions. Scatter in K factor values was even greater at elevated temperatures (Figure 20) than that observed for the W+0.6Cb alloy.

A major problem with the 92-6-2 alloy has been the condition of the as-extruded surface, which was usually rated from fair to poor. Some surface flaws extended deep enough to preclude any possibility of obtaining material for subsequent workability operations. Examples of 92-6-2 extrusions originating from 3½-inch ingots are shown in Figure 21. Also, a number of extrusions contained internal cracks similar to those shown in Figure 22. Cracks which appear to follow extrusion flow lines and which show crumbling or other evidence of relative motion at the interface were apparently present in the billet prior to extrusion. While cracks may have occurred during heating to extrusion temperature or during billet upset in the container, it is most likely that they were present in the ingot prior to billet machining. Additional precautions were taken to avoid thermal shock during cooling of the ingot in the furnace after melting was completed. Throttling the mold cooling water to a trickle soon after melting was completed is believed to have contributed significantly toward eliminating this problem. Cracks of a different type were present in other 92-6-2 extrusions which did not follow flow lines and were quite fine, showing no crumbling along the edges. These cracks are believed to have occurred after extrusion was completed, although no direct evidence is available to support this conclusion.

Extrusion surface defects were believed to be a function of ingot surface and/or arc melting practice, where ingot defects extended deep enough below the surface to preclude their complete removal by machining to billet diameter. It

was thought that a 4-inch ingot would be of sufficient diameter to contain surface defects in the layer removed by machining, so the arc furnace water jacket was modified to accommodate 4-inch molds and the balance of the 92-6-2 ingots (beginning with VA-94) was made in the larger molds. Electrodes measuring 1-3/4 inches in diameter were ordered for these ingots and the characteristics of this material are shown in Table 5. More melting current was required to obtain a smooth surface on a 4-inch ingot, and 6300 to 6500 amperes was used instead of the 5500 to 5800 amperes which seemed satisfactory for the 3½-inch ingots. A representative melting record for the production of 4-inch ingots is shown in Table 10.

Changing to the 4-inch diameter ingot resulted in more material losses by machining without significantly improving extrusion surfaces. Examples of extrusion produced from 4-inch ingots are shown in Figure 23. All extrusions after 943 (Table 9) were made from billets originating from 4-inch ingots.

The 92-6-2 alloy is more sensitive to failure from thermal stresses than is the W+0.6Cb alloy. It was found in several instances during the investigation of W+0.6Cb, that extrusions which did not clear the die and were subjected to rapid cooling in the runout tube were still sound and suitable for workability evaluation. The original 88-6-6 alloy could not be obtained as sound ingots because stresses developing during cooling would cause severe cracking, and reducing the columbium content from six to two percent has not completely overcome this problem.

As was the case with the W+0.6Cb extrusions, the dimensions of the 92-6-2 alloy bars increased from nose to tail due to die wear. Dimensions, in inches, of several 92-6-2 extrusions are as follows:

Extr. No.	Extrusion Temp., °F	Nose	Center	Tail
911	3800	1.484	1.485	1.492
912	4000	1.481	1.491	1.494
913	4000	1.223	1.223	1.230
914	4200	1.493	1.502	1.520
915	4200	1.150	1.154	1.162
926	4000	1.473	1.475	1.493
927	4000	1.490	1.491	1.502
928	4000	1.494	1.494	1.496
943	4000	1.499	1.503	1.517
1008	3800	1.484	1.488	1.488
1009	4000	1.505	1.505	1.510

It is difficult to relate directly the die wear caused by extrusion of the 92-6-2 alloy to that measured during extrusion of W+0.6Cb because the above tabulation contains a predominance of 4:1 extrusions while similar data for W+0.6Cb reported previously shows a predominance of 6:1 extrusions. Considering that 4:1 extrusions require less pressure and the distance between nose and tail measurements is about 2/3 that of 6:1 extrusions, the 92-6-2 alloy causes considerably more die wear than a superficial comparison of data indicates. It is not certain whether the effect on dies is simply a function of the 92-6-2 alloy's increased resistance to deformation or whether it is related to the poor surfaces of the 92-6-2 extrusions.

The flame-sprayed zirconia coating applied to steel dies is believed to be a most significant development contributing toward successful high temperature extrusions; however, variation in die design as it might further improve the process has received scant attention. Figure 24 shows the die designs used during this investigation. The dimensions to which the dies are machined are shown, and the indicated ratios are obtained after application of a 30-mil coating of zirconia. Unserviceable dies can be reclaimed by removing all of the old coating and applying a new layer.

An effort to improve die lubrication involved the addition of molybdenum disulphide to the zirconia during the flame spraying step. The coating spalled from the die during a trial steel extrusion, indicating that the MoS_2 interfered with the adherence of the ZrO_2. No 92-6-2 extrusions were attempted with this type of die.

The effect of extruding through rectangular dies is not obliterated by data scatter and Figures 7 and 20 clearly indicate that more pressure is required to produce rectangular cross-sections. The effects of non-uniform deformation, greater die surface, and variable entry angle are significant but difficult to isolate for separate study. Three round extrusions were made using dies with entry cones greater or less than 90 degrees, but extrudability differences were not great enough to be indicated by K factor data, and this study was abandoned because die load tooling was not available until near the end of the investigation and no billets were available for this determination. It is interesting to note that the 60° die did not increase the pressure required to produce W+0.6Cb extrusion 742 although it was expected that die friction would increase appreciably as die entry angle was decreased to this value. No difficulties or advantages were noted when producing W+0.6Cb extrusion 744 with a 100 degree die or 92-6-2 extrusion with a 120 degree die.

Hardness data from several 92-6-2 extrusions are shown in Table 11. Hardness variation across the section and along the length of the extrusion was not significant. Although the 92-6-2

alloy shows ample evidence of being more resistant to deformation than the W+0.6Cb alloy over a wide range of temperatures, room temperature hardness data indicates that it has less resistance to hardness indenter penetration.

Specimens were cut from several extrusions for machining into tensile specimens (see Figure 25). The specimens shown in Figure 26 contained a fairly large amount of recrystallization which accounts for the relatively low values obtained at 3000°F in vacuum. These data are shown in Table 12.

Extrusions 941 and 942 were produced using graphite nose and follower blocks heated to 2800°F instead of the usual 1600°F steel nose plug and the room temperature follower block. This was done to reduce the breakthrough tonnage by decreasing the amount of billet heat lost to the nose plug, and to reduce the force required to push the tail of the extrusion through the die because of heat lost to the cold follower block. Stem load traces indicated that the shape of the extrusion curve was not changed appreciably, in fact the breakthrough tonnages were higher than normal. No additional work was done with heated graphite nose and follower blocks.

In an attempt to overcome the difficulty with poor extrusion surfaces, and to experiment with a substitute for glass as a lubricant, some of the 92-6-2 billets were machined to a smaller diameter to enable their use with copper, steel, and molybdenum jackets. One billet was extruded using a copper jacket and two each were extruded with steel and molybdenum jackets. The copper and steel cans were painted with 9776 glass on the inside, inserted into the container, and allowed to reach container temperature (800°F). The copper jacket was used with extrusion 1042 and it did not affect the K factor nor improve the extrusion surface. Judging from the copper in the runout tube, this jacket melted quickly and squirted from the die under high pressure. The steel jackets used with extrusions 1045 and 1047 lowered the K factor somewhat (although this may have been a function of reduced billet diameter) but the surface of the extrusions were very poor.

The molybdenum jackets had a high enough melting point to permit being heated with the billet. Although these billets were extruded without any glass coating, the K factor values were very low (Figure 20). The same die was used for both extrusions and was in excellent condition afterwards. Some pressure reduction was undoubtedly due to the reduction in billet diameter required for accommodation of a 1/8-inch jacket. A number of bulges and cracks in the jacketed extrusion indicated that a poor surface was underneath, and removal of the jacket confirmed this observation.

The 92-6-2 alloy did not recrystallize as readily as the W+0.6Cb alloy. The microstructures of several extrusions are shown in Figures 27 and 28. The structures in Figure 28 were photographed at lower magnification to show that alternate bands of wrought and recrystallized structure are present. It was noticed during preparation of samples that some relief, or unevenness of surface, was present after electropolishing and etching. These ridges were believed to result from segregation, and the areas of varying composition were elongated during the extrusion process. These regions reacted at different rates when subjected to polishing and etching. This condition also favors bands of recrystallized and wrought structure. To avoid this inhomogeneity, better arc melting practices must be established and long time, high temperature heat treatments of these ingots should be investigated.

F. Lubrication Evaluation

While nearly all of the refractory alloy billets extruded up to this time have been coated with a glass that has the desired viscosity at billet temperature, it appears that the actual lubrication value of the glass is not significant under the conditions of extrusion in the high temperature range used for tungsten base alloys. Except for the possible benefits the coating affords in retarding oxidation losses and lessening billet heat dissipation, the use of glass often may be deterimental to the extrusion process.

The choice of a glass composition for application to a billet has depended entirely on the temperature to which the billet will be heated for extrusion. Since glass viscosity is temperature-dependent, a composition with too low a softening temperature will flow to the base of the billet during heating. This will cause the billet to stick to the zirconia pedestal block so that both the block and the thermocouple may be destroyed when the billet is removed. Also, the apparent increase in billet diameter at the base caused by an accumulation of displaced glass makes it difficult to manually insert the billet into the container.

To compensate for the thickness of the 30-mil coating normally applied, billets are machined to a smaller diameter than would be necessary if a coating were not used. Before the billet begins to extrude, it is upset to container diameter by ram pressure. In the initial stage of upset, the billet bulges in the center until it contacts the container, and as the billet approaches container diameter, the lubricant is progressively squeezed toward the ends. The glass forced to the rear of the billet is removed from the region where lubrication is needed and it may even increase frictional

effects when it becomes mixed with the graphite follower block and is chilled. The material machined from the billet diameter to compensate for glass coating thickness permits a large amount of deformation as the glass is squeezed from the center, a condition likely to initiate failure inside the billet and/or cause propagation of minor flaws in the billet surface.

Inasmuch as certain glasses require high temperatures before they become fluid enough to lubricate, it follows that they must be maintained at high temperatures during the extrusion process to function as lubricants. The container of the extrusion press is limited to a temperature range of 900 to 1000°F by the nature of the heating elements and the properties of the steel. The high temperature glasses are rigid and abrasive at this temperature. The higher the softening temperature of the glass, the thicker will be the non-lubricating layer between billet and container. A glass that is liquid at container temperature but viscous enough at extrusion temperature to preclude running off the billet would be ideal for this process but is not available.

Some of the K factor data scatter reported in this investigation is believed to result from various effects caused by the use of high temperature glass. No ingots of 92-6-2 were extruded without a glass coating, but the W+0.6Cb billet used to produce extrusion 1050 (see Table 2 and Figure 7) was heated to 3800°F and extruded without applied lubrication. An oxide coating formed, however, during the heating process. Extrusion pressure was so low in this instance that extrusion of "bare" billets is worthy of further investigation. While the value of glass as a lubricant is doubtful under the conditions required for the extrusion of tungsten base alloys, the application of glass to the 92-6-2 billets is not related to the poor surfaces of the extrusions. The same lubrication techniques did not adversely affect the extrusion surfaces ofW+0.6Cb or other tungsten base alloys. The employment of copper, steel, and molybdenum cans, while reducing the effort required for extrusion, did not improve surfaces and in some cases affected the surfaces adversely. It appears that poor surfaces on 92-6-2 extrusions were more a function of the nature of the alloy and less a function of extrusion practice.

As mentioned previously, the use of copper and steel cans with the 92-6-2 alloy did not produce any significant improvement, but molybdenum jackets materially reduced extrusion pressure. Future studies should investigate plasma-sprayed coatings of pure molybdenum 30 to 60 mils thick to compare the suitability of this technique to the successful but expensive method of applying molybdenum cans.

VI. THERMAL-MECHANICAL EFFECTS

A. Forging

To obtain preliminary forging data on the W+0.6Cb alloy, portions of extrusions 750 and 752 were selected for study. This material was extruded through 4:1 dies at 3200 and 3800°F, respectively. Portions of the 1½-inch rounds were painted with Corning 7052 glass, heated to 2700°F, and "side forged" to blanks measuring 4 x 2½ x ¾ inches. These blanks were cut into smaller samples measuring approximately 1 x 1¼ x ¾ inches and annealed for one hour at 3400°F to insure complete recrystallization. Annealing conditions were based on the data contained in Table 13 which show the recrystallization behavior of W+0.6Cb in the as-extruded condition. The structures after recrystallization were essentially identical in spite of the difference in extrusion temperature.

No data were available on forging the W+0.6Cb alloy at temperatures below 1600°F, so samples from each extrusion were heated to 1000, 1200, 1400, and 1600°F and reduced 75% by forging. These samples were not glass coated prior to heating and specimen oxidation was found to be minimal at these temperatures. All samples forged in the 1000 to 1600 degree temperature range showed edge cracking, with the severity of cracking decreasing as forging temperature increased, so that only minor flaws could be observed in the samples forged at the highest temperature. The dies of the forge press were machined from an H-12 tool steel and were heat treated to 49-51 R_c. These dies showed the impression of the 1000°F samples and one die cracked during forging of the 1200°F samples. Although one forging die was destroyed, the balance of forging was completed by keeping the samples away from the cracked area.

Heat is extracted rapidly from the forging by the forge press and all samples were chilled as a result. All specimens forged between 1000 and 1400°F showed a large number of fine internal cracks when sectioned. It is not known whether this would have occurred if chilling were avoided by using heated dies and/or a forge hammer, and samples were cooled slowly to room temperature after forging, or whether samples would have cracked at these low forging temperatures and high reductions regardless of the precautions.

Reliable hardness data could not be obtained on any of these samples because the fine network of cracks caused crumbling around the impression. All hardness readings

were in the 55 to 65 R_c range which were obviously in error. It appears that obtaining major reductions by forging 1600°F has no practical value. The low temperature range may be useful for operations involving minor deformation, however, such as straightening extrusions or rolling samples where it is desired to keep oxidation losses at a minimum.

Additional pieces of round extrusions were side forged and annealed, as described previously, to obtain samples for determining the effects of forging to several reductions at 1600, 2000 and 2400°F. Two samples each from extrusions 993, 763, and 761 were used for this study. These three extrusions were made with 4:1 dies. Extrusions 993 and 763 were extruded at 4000°F and 761 was extruded at 3200°F. While the original extruded structures, shown in Figures 10 and 11, were quite different, the structures after side forging at 2700°F and annealing one hour at 3400°F were the same except that the recrystallized grain size of the 993 samples was somewhat larger.

The annealed samples were cut diagonally to produce wedges (Figure 29) and marked along the sloping surface so that percent reduction could be obtained from the original dimensions indicated by the markings. No glass coatingswere employed on samples during forging. Reductions from 20 to 80 percent were obtained with one stroke of the press. Some crack indications were present in both samples of 761 and one sample of 993. These cracks may have occurred as a result of cooling too rapidly from the annealing temperature. These specimens were used for determination of forgeability, effect of reduction on recrystallization behavior, and hardness. All samples survived the forging step without separating, although the original cracks were now more obvious. Edge cracking that occurred during the preliminary forging study at 1600°F was not present in the region reduced 80 percent in the wedge at this temperature, and except for the original defects already mentioned, forging at 1600, 2000, and 2400°F was satisfactory. Hardness data from these samples are shown in Table 14.

The samples were heated for one hour at 3000°F to determine the effect of forging temperature and reduction on recrystallization. Some of the recrystallized structures are shown in Figure 29. Only a small amount of wrought structure was detected in the samples, as recrystallization was essentially complete. Large grains existed in the portion of the sample reduced 20 percent and fine grains were present in the region of maximum reduction. Although grain size did not increase uniformly along the samples, the trend of the grain size relative to percent reduction was unmistakable.

The 92-6-2 alloy was forged also, but more rectangular extrusion stock was available and the pre-forging step was not necessary. Samples cut from the as-extruded bar were annealed at several temperatures for one hour to determine the effect of annealing on

hardness. Because of the scarcity of sound material, portions of extrusions 898, 899, and 900 were used for this study, since these data could be obtained on unsound material. The original structures are shown in Figure 26, and the effect of recrystallization temperature on structure is shown in Figure 30. Hardness data in Table 15 indicate that the material becomes somewhat softer as annealing temperature is increased. Estimated percent recrystallization resulting from annealing 1 hour at temperatures between 2600 and 3400°F are shown in Table 16 and samples for subsequent forging operations were annealed for one hour at 3400°F based on this data.

Preliminary forging studies, using 70% reduction, at 1200, 1700, and 2200°F indicated that 2200°F was the most favorable temperature, as other samples contained a large number of cracks. Samples of 92-6-2 forged at the three temperatures are shown in Figure 31.

The few large samples of rectangular extrusions that were sound enough for cutting into wedges were badly cracked after annealing and no additional forging studies were done on the 92-6-2 alloy.

B. <u>Rolling</u>

Only a small quantity of W+0.6Cb samples was available for rolling after other operations had been completed. Samples of W+0.6Cb round extrusions 761, 763, 992, and 993 were prepared by forging and annealing in the same manner as used when preparing samples for forging. Extrusion 759 was a rectangular extrusion and only the 3400°F recrystallization was needed. Although more care was observed in sample preparation, most of the pieces broke during early rolling passes. The 1600, 2000, and 2400°F temperatures used were less satisfactory for rolling than for forging, although better rolling results were obtained at the highest temperature. Rolling results are as follows:

Sample	Temp., °F	Initial Thickness	Final Thickness	Remarks
759	1600	.587	---	Cracked on first pass
759	2600	.589	.223	10 passes,minor cracks removed between passes
759	2400	.587	.125	12 passes,minor cracks removed between passes
761	2000	.709	.580	split on third pass
763	2000	.741	.680	split on first pass
763	2400	.742	.625	split on second pass
992	2000	.698	.563	split on third pass
993	2400	.748	.460	split on fourth pass

Most samples showed signs of failure during the first rolling pass and where it was practical to do so, defective areas were removed before further rolling was attempted. A common cause of failure in the samples forged from rounds and annealed was a tendency of the specimens to split in the center as it emerged from the rolls, so that two pieces half the desired thickness were obtained. Samples of extrusion 759, which was rectangular and required only a one hour anneal at 3400°F before rolling, showed a strong tendency toward edge cracking. Rolling was halted occasionally while cracks were removed by grinding or by cutting off the affected area. Examples of sample cracking are shown in Figure 32, and available hardness data are shown in Table 14.

The capacity of the rolling mill would not permit heavy reductions on initial passes, but a more successful product might have been obtained if the annealed specimens had been forged 40 percent or more before rolling was attempted. No material of the 92-6-2 composition was suitable for rolling.

C. Swaging

Swaging proved to be a useful method of reducing extruded sections of refractory alloys in order to evaluate the effect of a deforming operation on these materials. One is limited to a fixed set of reductions which are presently determined by available die sizes. The largest die will swage a bar to 1.188 inches. Subsequent swaging passes utilize 1.062, .937, .843, .750, .687, and .609-inch dies. Several smaller dies (to .375 inch) were not used for tungsten swaging because stock diameter was not suitable for tensile specimens.

Dies were machined from hot-work die steel (VASCO-M2) and heat treated to 48-52 R_c. The metal working portion of the dies measured 1½ to 2 times the diameter, which places them in the "finishing die" rather than the "working die" category, as they resemble the design commonly used for straightening. Die blocks were cleaned between passes using a toolmaker's grinder and emery paper to remove adhering tungsten oxide. Inspection after cleaning disclosed a number of circumferential cracks in the working surface of several dies after the first tungsten bar was swaged at 2700°F, however, this condition did not worsen noticeably after additional bars were swaged.

Both the W+0.6Cb alloy and the 92-6-2 alloy were checked for cracks prior to swaging by etching the end of the bar with a strong $HF-HNO_3$ solution and checking with dye penetrant. When cracks existed they were usually obvious enough after etching to make confirmation with dye penetrant unneccessary.

Current swaging practice at the Air Force Materials Laboratory entails heating the as-extruded bar in a Harrop portable Globar furnace or a Pereney Globar furnace and swaging with three to five minute reheats between passes. Annealing was done after first swaging to a diameter from which the .609-inch die will produce the desired reduction. Extrusion samples less than 7 inches long are difficult to handle because the length is insufficient to permit swaging to the center of the bar when the sample is inserted into the dies from either end. On the other hand, the internal dimensions of the two-mentioned furnaces will not allow reheating of bars more than 17 inches long because the furnace doors cannot be closed. The bars must be slowly cooled, cut to shorter lengths, and reheated before swaging can proceed.

Sections of W+0.6Cb extrusions 974, 994, 995 and 997 were used for swaging evaluation. Swaging samples were removed from the above extrusions according to the diagram on Figure 15. In order to evaluate the effect of swaging on the as-extruded surface, the only pre-swaging preparations made were to sandblast the sample and remove serious defects by cutting off the affected portion of the bar. If surface preparation had been considered necessary, a single swaging pass would have been required to straighten the extrusions sufficiently to allow machining in a lathe.

Samples from extrusions 974, 995, and 997 were heated 30 minutes at 2700°F and swaged from the nominal 1.2-inch extrusion diameter to .937 inch in two passes. Sample 994 was heated to 2400°F for 30 minutes and swaged to .843 inch in three passes. Three to five minutes were allowed for reheating between each pass. No difficulties were encountered in any of these operations, however, it was noted that the material heated to 2400°F was more difficult to feed manually into the dies.

In view of the additional reduction of the as-extruded section, which previously had recrystallized completely after one hour at 3200°F (Table 13), it was assumed that the extruded and swaged material also would recrystallize completely under these conditions. After subjecting specimens 994, 995, and 997 to this annealing treatment, it was discovered that the recrystallization was only about 90 percent complete. Specimen 974 was annealed at 3400°F for one hour which resulted in complete recrystallization and even produced some grain growth.

Samples 974, 995, and 997 were swaged to .609-inch bar stock at 2700°F, and a sample of 995 was swaged to .609 inch at 2400°F, which reduced the annealed structure 60 percent in four passes. Sample 994 was swaged from .843 to .687 at 2200°F, a reduction of 35 percent. Some microstructures of annealed and swaged samples are shown in Figure 33.

The appearance of the as-swaged surface of the .609-inch stock was superior to that of the original as-extruded samples. This was due in part to the nature of the dies, although most of the improvement occurred as a result of oxidation in the furnace and during transfer to and from the swaging machine. The volatility of the oxide enabled removal of the outer layers of material containing the minor surface defects.

Swaging of W+0.6Cb bars had been done previously at the Westinghouse Materials Manufacturing Division, Blairsville, Pennsylvania[3]. These samples were essentially the same size as those just described, but the heating to 2800°F was necessary before the operator could force the material through the dies manually. The apparent difference in swageability was a result of different die designs. The dies used for swaging at Blairsville used a 20 degree entrance angle while the 12 degree entrance angle employed in the Fenn dies at the Air Force Materials Laboratory allowed swaging of W+0.6Cb alloy as low as 2200°F.

Two bars of 92-6-2 alloy were found suitable for swaging. Extrusion 1028 was swaged at 2700°F from the original 1.17-inch diameter to .609 inch without an annealing step. Three-inch sections were cut from the rod and two of the four samples showed internal cracks. One sample was machined into a tensile specimen and the other was annealed one hour at 3400°F before machining into a specimen. Tensile data on the 92-6-2 alloy are shown in Table 12. Extrusion 1043 appeared suitable for swaging and withstood reduction to .937 inch, a one hour anneal at 3400°F, and further reduction through the .843-inch die. The bar began to break into several pieces while it was being worked in the .750-inch die and swaging was discontinued. Microstructures of swaged 92-6-2 are shown in Figure 34.

The results of the high temperature tensile tests of the swaged W+0.6Cb is shown in Table 17, and test results on other samples of wrought W+0.6Cb alloy are shown for comparison. The data in Table 17 indicate that swaging temperature does not appreciably affect high temperature tensile properties, at least in the range of swaging temperatures used. Air Force Materials Laboratory personnel[9] obtained appreciably higher strength values by forging samples between 40 and 54 percent at 2675°F and machining round samples from the center. Of particular significance is that their samples were maintained at 3000°F for 15 minutes before stress was applied, while the sample tested by Union Carbide[2] was held at temperature for only five minutes.

VII. MAXIMUM YIELD EFFORT

A variety of billets have been extruded for other agencies having government contracts that involve extrusion of refractory and other alloys. One of the alloys of which a large number of billets have been extruded was a sintered Cr+MgO composite developed by the Bendix Corporation. The composite, designated as "Chrome-30", contains 93.5 percent chromium, 0.5 percent titanium and 6.0 percent magnesium oxide.

From the data compiled in Table 18, it is noted that this alloy may be extruded easily using temperatures as low as 2000°F and extrusion ratios as high as 12:1. This alloy had been extruded at 12:1 at 2000°F during Part I of this investigation[1]. Extrusion surfaces were generally very good and die life was considerably longer than it was with refractory alloys. Details on subsequent working operations and property data are contained in ASD-TDR-63-297 "Development of Chromium Composite Alloy with High Temperature Oxidation and Erosion Resistance".

A number of molybdenum base billets were extruded and data from this work are summarized in Table 19. K factor data are plotted in Figures 35 to 37. The extrudability reference line for the molybdenum-base extrusions was obtained from data gathered during Part I of this investigation, where a large number of TZM (Mo+0.3Ti+0.1Zr) billets were extruded over a wide temperature range.

Nine molybdenum-base billets were extruded into tubing for the Atomic Energy Commission. Conventional 6:1 round dies were used with ¾-inch zirconia coated mandrels, which changed the ratio to 8.8:1. Billets measured 2.945 inches in diameter by five inches long and contained a one-inch bore through which the mandrel was inserted just prior to extrusion. Because of fairly large tolerances, billets were supplied in wrought form to reduce the chance of billet failure during upset which was more likely to occur if arc-cast material was used.

No press modifications were necessary to enable the extrusion of tubing. A sketch of the billet, follower block, mandrel, and dummy block is shown in Figure 38. Ram pressure applied directly to the dummy block forces the mandrel through the die with the extrusion, and the press "bottoms out" before the tapered portion of the mandrel reaches the die orifice. The only difficulty encountered with this arrangement was the inability of the graphite to push the tube off the mandrel after it had emerged from the die. Tapping the mandrel out of the tube afterward would cause the zirconia mandrel coating

to spall, otherwise the mandrels could have been reused without recoating.

Several of the AEC billets (extrusions 1057 to 1060) employed pyrolytic graphite as a canning material to reduce extrusion effort. The graphite jackets were inserted into the container and allowed to reach container temperature while billets were being heated. Billet bulge during upset forced the graphite away from the center so that it was trapped at the billet ends, spoiling the surface of the nose and tail of the extrusions. The use of graphite cans did not materially affect extrusion pressures. Except where graphite had an adverse effect, the surfaces of all tubing extrusions were good, particularly the interiors.

Most of the tungsten-base billets extruded during this part of the program were molybdenum jacketed. The particular significance of molybdenum jacketing becomes apparent when comparing K factor data from billets that were extruded during Part I of this investigation but were not jacketed. The data obtained from extruding four tungsten base compositions are plotted in Figure 39, and the data from Table 20 of the same compositions extruded with 1/8-inch thick molybdenum jackets is plotted also for comparison. While the extrudability of each of these alloys, relative to one another, is very similar with or without jackets, the very significant reduction in the pressure required to accomplish extrusion is obvious when jackets were used. The 10 percent reduction in billet cross-section resulting from machining the billets to a smaller diameter so the jackets can be used does not wholly account for the differences in extrudability. The information in Table 20 indicates that all the jacketed extrusions exhibited good surfaces, however this observation was based on the surface condition of the extruded jacket only, as no opportunity was available to inspect what lay beneath this covering. In the case of the 92-6-2 jacketed extrusions mentioned earlier, it was found that a relatively smooth jacket could conceal flaws in the extrusion.

Data obtained on sintered and arc cast unalloyed tungsten (Table 20) was plotted in Figure 40, and data from unalloyed tungsten billets extruded during a previous investigation[10] are plotted in Figure 40 for comparison. Considerable differences in extrudability of "unalloyed" tungsten exists, depending on billet source.

The centerlines of the K factor bands of the W+0.6Cb and 92-6-2 alloys were shown in Figure 41 for reference to compare alloy extrudability. If jacketing affected the extrudability of the W+0.6Cb alloy as it did other compositions, a much wider temperature and extrusion ratio range is available for investigation.

VIII. INTERNAL SUPPORT PROGRAM

Extrusions produced in this portion of the program were to support the project requirements of the Air Force Materials Laboratory in work areas not directly applied to this contract and the data from this work are contained in Table 21.

The tungsten base ingots produced during the arc melting investigation were extruded as part of the internal support program and the complete evaluation is given in ASD-TDR-63-296. Data on W+0.6Cb ingots pertinent to this program are included in the discussion of W+0.6Cb in this report. Several of the W+0.6Cb billets contained minor additions of titanium and zirconium, and the effect of these additions on extrudability are shown in Table 21, extrusions 946, 947, 955, 964 and 965. It will be noted that adding zirconium to the alloy decreases extrudability while adding titanium has the opposite effect, the reason being that zirconium is not lost to any degree while melting and becomes a solid solution hardener, while titanium is almost completely eliminated and the alloy is purified in the process. In order to evaluate the effects of arc melting, nearly all extrusion for the arc melting contract was done at 3800°F with 6:1 dies. The data in Table 21 indicate that fair to poor extrusion surfaces resulted occasionally when arc melting and extrusion variables were not suited to one another.

Five columbium base billets were extruded at 3000 and 3200°F with 10:1 dies. This material did not extrude well and most of the extr.sions exhibited a large number of circumferential cracks. This was believed to be a function of material oxidation during heating. The application of a protective coating (other than glass) is recommended; and, since extrusion pressures were not close to the limit, it would be advantageous to reduce billet temperatures as well. Billet surface effects masked the significance of adding tungsten and molybdenum to columbium.

Air Force Materials Laboratory personnel are currently engaged in a temperature-friction study using the die pressure load cell and the temperature-sensing device described earlier. Most of this work has been done on 1018 steel billets because of their low cost and availability. Considerably less tonnage is measured at the die than at the base of the billet in many cases, and the tonnage differential was influenced strongly by lubrication practice. Data from the temperature-sensing device clearly shows the difference in temperature between the center of the billet and the ends, although this device may not be

as useful for measuring variations in temperature of refractory alloy extrusions because of interference of volatile oxides.

IX. REFERENCES

1. Carnahan, D. R., and Visconti, J. A., Extrusion, Forging, Rolling, and Evaluation of Refractory Alloys; Westinghouse Electric Corporation, ASD-TDR-62-670, October, 1962.

2. Investigation of the Properties of Tungsten and Its Alloys; Union Carbide Metals Company, Division of Union Carbide Corporation, Niagara Falls, N.Y. WADD-TR-60-144, May, 1960.

3. Reimann, G. A., Vacuum Arc Melting of Tungsten + 0.6 Columbium; Westinghouse Electric Corporation, ASD-TDR-63-296, April, 1963.

4. Westgren, R. C., and Reynolds, W. T., Research on Workable Refractory Alloys of Tungsten, Tantalum, Molybdenum, and Columbium; Crucible Steel Company of America, Pittsburgh, Pennsylvania WADD-TR-61-134, April, 1961

5. Reimann, G. A., Vacuum Arc Melting of a Tungsten Alloy (Tungsten - Molybdenum - Columbium); Westinghouse Electric Corporation, ASD-TDR-62-781, August, 1962.

6. Pierce, C. M., Unpublished work used for basis of theoretical discussion.

7. Pierce, C. M., and Air Force Materials Laboratory personnel, private communication, to be published.

8. Pearson, C. E., and Parkins, R. N., The Extrusion of Metals, John Wiley and Sons, Inc., New York. 2nd ed., 1960, p. 204.

9. DePierre, Vincent, and Saul, George, Effects of Thermal-Mechanical Processing Variables on 3000°F Short-Time Tensile Properties of Tungsten + 0.6% Columbium Alloy; Aeronautical Systems Division, ASD-TDR-63-782, August, 1963.

10. Tombaugh, R. W., Green, R. C., Gehrke, J. H., Development of Optimum Methods for the Primary Working of Refractory Metals; Harvey Aluminum Inc., WADD-TR-60-418 Part II, August, 1961.

TABLE 1

W+0.6Cb BILLET ANALYSES AND HARDNESS

	Wah Chang						Oremet	
	31015		31192		31202			
Ingot	Top	Bottom	Top	Bottom	Top	Bottom	OM1523-1	OM1523-3
Columbium	0.68%	0.69%	1.19	1.20	1.27	1.27	0.50%	0.87%
Carbon	*30	*30	*30	*30	*30	*30	*20	*20
Oxygen	80	70	*50	*50	*50	*50	30	*20
Nitrogen	25	15	20	52	54	40	--	--
Hydrogen	1.0	1.1	0.6	0.6	0.9	0.8	--	--
	Residual Metallic Impurities							
Al	*20	*20	*20	*20	*20	*20		
B	1.5	1	2.5	4.0	2.0	2.0		
Cd	*5	*5	*5	*5	*5	*5		
Co	*20	*20	*20	*20	*20	*20		
Cr	*20	*20	*20	*20	*20	*20		
Cu	*40	*40	*40	*40	*40	*40		
Fe	*100	*100	*20	*20	*20	*20		
Mg	*20	*20	*20	*20	*20	*20		
Mn	*20	*20	*20	*20	*20	*20		
Mo	25	25	50	50	60	50		
Ni	*20	*20	*20	*20	*20	*20		
Pb	*20	*20	*20	*20	*20	*20		
Si	*100	*100	*100	*100	*100	*100		
Sn	*20	*20	*20	*20	*20	*20		
Ti	*20	*20	*20	*20	*20	*20		
V	*20	*20	*20	*20	*20	*20		
Zr	*50	*50	*50	*50	*50	*50		
Rockwell A Hardness	64-66 (64 Avg.)		65-68 (66 Avg.)		64-67 (65 Avg.)		65 (Avg.)	

All analyses reported in parts per million unless indicated otherwise.
*Indicates that actual values are less than values shown.
Analytical results were supplied by Wah Chang and Oremet.

TABLE 2

SUMMARY OF W+0.6Cb EXTRUSION DATA

Extr. No.	Ingot No.	Source	Billet Size (Dia.x Length) (inches)	Billet Weight (lb.)	Glass*	Extr. Temp. (°F)	Ratio	Max. Force (tons)	Min. Force (tons)	Peak "K" Factor	Extrusion Dimensions (inches)	Yield (%)	Remarks
992	31015T	WC	2.945 x 4.313	20.3	7900	3800	4.3:1	410	350	76,000	1.483 dia.	66	Gd surface
993	31015B	WC	2.941 x 4.563	21.2	7900	4000	4.3:1	390	320	72,400	1.479 dia.	70	Gd surface
994	31202	WC	2.949 x 4.500	21.3	7900	4000	7.4:1	520	440	70,600	1.130 dia.	85	Gd surface
995	31192B	WC	2.946 x 4.750	22.3	7900	3800	6.6:1	450	410	64,300	1.193 dia.	85	Gd surface
996	31192T	WC	2.947 x 4.313	20.1	7900	4000	6.4:1	500	430	72,500	1.210 dia.	80	Pr surface
997	OM1523-3	OM	2.950 x 4.625	21.6	7900	3800	6.5:1	560	480	80,800	1.204 dia.	80	Pr surface
896	VA-68	AFML	2.944 x 3.625	16.9	7810	3800	6.2:1	740	---	------	----- ----	--	Stuck
935	VA-78	AFML	2.942 x 4.813	22.8	7810	3800	6.4:1	515	470	75,000	1.208 dia.	--	VG surface
936	VA-79	AFML	2.940 x 4.938	23.1	7810	3800	8.4:1	590	560	75,000	1.060 dia.	--	VG surface
948	VA-83U	AFML	2.941 x 5.000	23.2	7810	3800	6.4:1	720	---	------	----- ----	--	Stuck
951	VA-83L	AFML	2.941 x 5.000	23.1	7900	4200	3.0:1	620	---	------	----- ----	--	Stuck
956	VA-86	AFML	2.937 x 5.000	23.0	7810	3800	6.4:1	500	430	72,700	1.215 dia.	--	Gd surface
957	VA-87	AFML	2.942 x 5.000	23.1	7810	3800	6.4:1	630	---	------	----- ----	--	Stuck
958	VA-88	AFML	2.944 x 5.031	23.4	7810	3800	6.4:1	590	---	------	----- ----	--	Stuck
966	VA-91	AFML	2.940 x 4.983	23.0	7810	3800	6.4:1	640	---	------	----- ----	--	Stuck
974	VA-92	AFML	2.938 x 5.031	23.2	7810	3800	6.3:1	570	400	83,800	1.220 dia.	--	Pr surface
337	2697	UC	2.974 x 4.500	20.2	7740	3400	4.1:1	528	440	102,000	1.328 dia.	--	Gd surface
448	KC950	UC	2.930 x 5.188	23.8	7740	3000	4.3:1	570	485	105,400	1.913 x .925	--	Gd surface
449	KC947	UC	2.950 x 6.875	27.0	7740	3200	6.0:1	665	---	------	------------	--	Stuck
632	KC1079	UC	2.935 x 5.875	26.8	7900	4000	4.4:1	490	390	89,400	1.866 x .934	90	Fr surface
742	KC1139A	UC	2.934 x 4.500	21.7	7900	4000	7.5:1	540	475	72,500	1.126 dia.	87	Fr surface, 60° die
743	KC1139B	UC	2.936 x 4.688	21.8	7900	4000	6.3:1	555	480	81,400	1.225 dia.	85	Gd surface
744	KC1142A	UC	2.932 x 4.750	21.8	7900	4000	7.2:1	545	510	74,500	1.141 dia.	93	Gd surface, 100° die
746	KC1143A	UC	2.942 x 4.750	22.0	7900	4000	4.0:1	385	350	74,700	1.330 dia.	78	Fr surface
747	KC1143B	UC	2.942 x 4.750	21.8	7900	4000	7.9:1	580	480	76,000	1.093 dia.	80	Gd surface
750	KC1136B	UC	2.934 x 4.688	21.6	7740	3200	4.0:1	495	450	96,000	1.537 dia.	82	Gd surface
751	KC1137B	UC	2.933 x 4.438	20.6	7740	3200	8.1:1	---	---	------	----------	--	Stuck
752	KC1138A	UC	2.934 x 4.750	21.8	7810	3800	4.1:1	420	410	80,500	1.518 dia.	89	Gd surface
753	KC1138B	UC	2.936 x 4.688	21.8	7810	3800	7.6:1	620	600	82,500	1.116 dia.	80	Fr surface

TABLE 2 (continued)

Extr. No.	Ingot No.	Source	Billet Size (Dia.x Length) (inches)	Billet Weight (lb.)	Glass*	Extr. Temp. (°F)	Ratio	Max. Force (tons)	Min. Force (tons)	Peak "K" Factor	Extrusion Dimensions (inches)	Yield (%)	Remarks
754	KC1148A	UC	2.934 x 4.375	20.2	7740	3200	4.5:1	590	495	106,000	1.900 x .900	89	Fr surface
755	KC1146A	UC	2.934 x 4.750	22.0	7810	3800	4.4:1	480	450	87,500	1.866 x .935	90	Gd surface
756	KC1146B	UC	2.934 x 4.250	20.7	7810	3800	5.5:1	530	495	84,400	1.903 x .736	92	Gd surface
757	KC1137A	UC	2.929 x 4.625	21.4	7810	3800	6.7:1	620	560	87,400	1.874 x .620	92	Fr surface
758	KC1147A	UC	2.936 x 4.250	20.2	7900	4000	4.5:1	400	350	71,800	1.850 x .910	89	Pr surface
759	KC1147B	UC	2.936 x 4.750	22.0	7900	4000	7.0:1	590	480	82,000	1.859 x .595	95	Gd surface
761	KC1136B	UC	2.934 x 4.688	21.6	7740	3200	4.0:1	510	460	98,700	1.534 dia.	78	Gd surface
762	KC1145B	UC	2.935 x 4.750	21.8	7810	3800	4.2:1	480	375	90,800	1.494 dia.	70	Gd surface
763	KC1145A	UC	2.935 x 4.750	21.8	7900	4000	4.1:1	380	340	73,400	1.529 dia.	66	Gd surface
772	KC1140B	UC	2.933 x 4.750	22.0	7913	4200	5.9:1	570	500	86,800	1.265 dia.	90	Gd surface
1050	KC11841B	UC	2.929 x 3.875	17.8	None	3800	6.2:1	500	460	74,000	1.234 dia.	83	Gd surface

Surfaces rated according to standard established in Figure 13.

Sources:
WC Wah Chang Corp.
OM Oregon Metallurgical Corp.
AFML Air Force Materials Laboratory
UC Universal Cyclops Steel Corp.

*Corning glass numbers
Billet end shape, 0.25" x 45° bevel
Nose block, 1018 steel coated with 8871 glass and heated to 1600° F
Follower block, machined graphite
Extrusion dimensions obtained at nose sample

TABLE 3

W+0.6Cb BILLET ANALYSES

(data from previous investigations)[a]

Billet Number	Extrusion Number	%Cb	ppm C	ppm O	ppm N	ppm H	ppm Fe	ppm Mo
KC 1072	632	.54	21	5	13	1	9	20
KC 1136	750, 761	.64	10	6	10	*1	15	98
KC 1137	751, 757	.62	27	12	11	*1	2	50
KC 1138	752, 753	.62	44	12	10	*1	1	64
KC 1140	772	.84	10	15	21	1	*1	40
KC 1143	746, 747	.52	20	5	20	1	1	*10
KC 1145	762, 763	.56	50	12	24	2	1	*10
KC 1146	755, 756	.63	45	20	14	2	5	*10
KC 1147	758, 759	.64	60	14	18	2	5	*10
KC 1148	754, 1050	.54	43	10	26	2	5	*10
VA-68	896	.58	44	9	8	8.3	5	--
VA-78	935	.68	10	17	22	1	10	--
VA-79	936	.74	18	9	14	*1	15	25
VA-83	948, 951	.69	123	8	13	3.7	10	30
VA-86	956	.66	6	21	6	1	10	20
VA-87	957	.57	51	25	12	1.8	10	60
VA-88	958	.62	226	15	20	2.1	10	20
VA-91	966	.56	230	28	19	1.8	10	40
VA-92	974	.57	25	12	12	2	30	40

Residual Metallic Impurities
(approx. same on all billets)

Al	*10	Cu	*10	Ni	*10
Cr	*10	Mg	*10	Si	30 to *10
Co	*10	Mn	*10	Ti	*1

(a) ASD-TDR-62-670, ASD-TDR-63-296

* Indicates that actual values are less than values shown.

KC series billets analyzed by Universal Cyclops Corporation, Bridgeville, Pa.

VA series billets analyzed by Le Doux, Inc., Teaneck, N.J.

TABLE 4

W+0.6Cb EXTRUSION HARDNESS

(Average of 3 Rockwell A Readings)

Extr.	Nose		Center		Tail	
No.	Edge	Center	Edge	Center	Edge	Center
992	72.3	72.7	72.3	72.7	72.7	73.0
993	74.0	72.3	71.0	71.3	73.3	74.3
994	74.3	72.0	71.0	71.0	73.7	74.3
995	73.0	73.2	70.0	70.0	72.0	70.5
996	73.0	72.0	70.0	71.0	73.5	72.5
997	73.0	74.0	72.0	72.0	71.0	71.0
935	71.3	70.7	69.7	70.0	73.0	73.0
936	68.7	69.0	69.7	70.3	72.7	72.0
956	69.3	69.3	69.3	69.7	72.0	71.0
974	72.3	71.0	69.7	70.0	72.7	73.0
738	71.3	71.3	71.0	69.7	73.0	72.7
742	72.0	71.7	70.7	70.3	71.7	72.0
743	70.7	71.3	71.3	70.7	72.0	72.0
750	72.7	71.7	71.7	71.3	73.7	74.0
752	71.3	71.3	70.0	69.7	71.7	72.0
762	73.0	72.0	71.0	71.3	72.7	71.0
763	71.7	71.7	69.0	69.7	72.0	72.0

TABLE 5

SUPPLIER'S DATA ON 94W+6Mo ELECTRODES

Material information on electrodes used to produce 3½-inch (lot 09227)and 4-inch (lot 01310) ingots in AFML furnace.

1. Spectrographic Powder analysis (ppm)

	09227	01310		09227	01310
Al	*10	*10	Mn	*10	*10
Ca	*10	*10	Mg	*10	*10
Cr	*10	*10	Ni	*10	*10
Cu	10	*10	Si	10	10
Fe	10	10	Sn	*10	*10

2. Processing History

The material was processed according to a schedule consisting of hydrostatic pressing and hydrogen furnace sintering to a temperature above 1800°C.

3. Density (percent of a theoretical density of 18.32/cc) and weight (lb.) of electrodes.

Electrode	Density	Weight	Electrode	Density	Weight
09227-1	92.0	28.0	01310-1	91.1	34.5
-2	92.1	30.5	-2	91.2	41.0
-3	92.0	28.0	-3	91.0	40.0
-4	92.6	28.5	-4	91.0	40.0
-5	92.0	28.0	-5	91.6	39.0
-6	92.4	30.0	-6	90.9	33.5
-7	92.0	25.5	-7	91.6	39.0
-8	92.4	25.0	-8	91.0	40.0
-9	92.0	28.0	-9	91.0	40.0
-10	92.0	28.0	-10	91.3	25.0
-11	92.2	29.0	-11	91.7	22.0
-12	92.6	28.5	-12	91.4	38.0
-13	92.7	26.0	-13	91.0	40.0
-14	92.0	28.0	-14	91.6	39.0
-15	92.4	27.5	-15	91.4	21.0
-16	92.0	28.0	-16	91.2	33.0
			-18	91.3	35.5
			-19	91.4	17.0
			-20	91.3	29.0

Oxygen	16 ppm
Nitrogen	1 ppm
Hydrogen	1 ppm
Carbon	10 ppm

*Indicates that actual values are less than values shown.

TABLE 6

TYPICAL MELTING RECORD OF W+6%Mo+2%Cb
(Using 3½ inch mold)

Heat number VA-73
Electrodes 09227-2, 09227-8
Electrode size 1.44 x 55.5"
Leak rate .5 micron per minute
Mold size 3.5 x 18"

Time Min.	Time Sec.	Amperes	Volts	Pressure (Microns)	Stirring (Amperes)	Electrode Travel (Inches)
0	0	4000	24	0.005	2	0
1	30	4800	28	-----	2	0
2	20	5200	28	0.08	2	-
3	00	5800	28	0.1	2	3½
8	00	5800	26	0.06	3	6
9	00	5800	27	0.08	3	9
11	10	5800	27	----	3	11
13	45	5300	28	0.06	1	15
16	45	5800	28	0.08	2	18
19	15	5800	28	0.07	1	22
22	00	5800	28	----	1	26
28	00	5800	28	0.05	1	30
30	25	5800	28	0.05	1	39
31	00	4600	--	0.03	½	--
32	15	2500	--	----	½	--
33	20	POWER OFF		0.03	-	--

TABLE 7

HARDNESS OF 92W+6Mo+2Cb BILLETS

Billet	BHN,* Top	BHN,* Bottom
VA-69	285	285
VA-70	280	290
VA-71	285	300
VA-72	290	272
VA-73	285	285
VA-74	272	285
VA-75	302	308
VA-76	295	320
VA-84	300	290
VA-94	272	285
VA-95	280	290
VA-96	302	308
VA-97	285	285
VA-98	285	300
VA-99	300	290

* 10mm tungsten carbide ball, 3000 Kg. load

TABLE 8

92-6-2 BILLET ANALYSES

Ingot Number		%Mo	%Cb	ppm C	ppm O	ppm N	ppm H
VA-69B	T	5.0	1.9	20	6	1	1
	B	5.1	2.0	20	4	1	1
VA-70T	T	4.7	1.8	20	3	1	1
	B	5.2	2.0	30	7	1	1
VA-70B	T	5.2	2.0	30	5	2	1
	B	5.0	2.1	30	12	3	1
VA-71T	T	2.9	1.5	30	4	1	1
	B	5.1	1.9	20	7	2	1
VA-71B	T	4.8	2.1	30	6	2	1
	B	4.8	1.7	10	4	1	1
VA-72T	T	4.3	2.0	10	5	2	1
	B	5.3	2.0	20	33	3	1
VA-72B	T	5.3	2.0	20	5	2	1
	B	5.1	1.9	20	--	-	-
VA-73T	T	4.7	1.9	--	8	1	1
	B	4.9	1.9	10	3	1	1
VA-73B	T	5.2	1.9	30	4	1	1
	B	5.1	1.6	--	4	1	1
VA-74T	T	4.9	2.1	30	--	-	-
	B	5.1	2.2	20	--	-	-
VA-74B	T	4.8	2.5	20	7	3	1
	B	5.2	2.0	20	5	2	1
VA-75T	T	3.7	1.7	10	8	2	1
	B	5.1	2.0	10	-	-	-
VA-75B	T	5.0	2.0	10	5	2	1
	B	4.9	2.1	20	-	-	-
VA-76T	T	5.6	1.8	20	3	1	1
	B	5.6	2.2	10	3	1	1
VA-76B	T	5.6	2.2	10	-	-	-
	B	5.1	1.8	10	4	2	1
VA-94	T	4.6	2.0	20	13	1	1
	B	5.2	2.0	30	10	2	1
VA-95	T	3.8	1.8	20	8	1	2
	B	5.3	2.0	50	17	3	2
VA-96	T	4.8	1.9	*10	10	1	1
	B	5.1	1.9	35	17	4	2
VA-97	T	4.3	1.8	*10	11	1	2
	B	5.3	2.1	15	7	1	2
VA-98	T	5.1	2.0	15	5	1	1
	B	5.5	2.0	20	6	1	1
VA-99	T	4.5	1.8	20	7	1	1
	B	5.2	1.9	15	10	2	1
VA-103	T	5.0	1.8	10	18	*5	*5
	B	5.4	1.8	35	8	*5	*5
VA-105	T	4.6	1.8	*10	8	*5	*5
	B	4.9	1.9	40	8	*5	*5
VA-106	T	4.1	1.7	15	6	*5	*5
	B	5.2	2.0	10	8	*5	*5
VA-107	T	5.2	2.1	25	6	*5	*5
	B	5.2	1.8	15	10	*5	*5
VA-108	T	4.4	1.7	25	7	*5	*5
	B	5.2	2.0	10	9	*5	*5
VA-109	T	4.6	1.9	25	4	*5	*5
	B	5.3	1.9	15	8	*5	*5
VA-110	T	4.9	1.9	35	7	*5	*5
	B	5.2	1.9	*10	11	*5	*5

Analyses by Westinghouse Electric Corporation, Blairsville, Pennsylvania.

*Indicates that actual values are less than values shown. T = top, B = bottom

TABLE 9

SUMMARY OF 92-6-2 EXTRUSION DATA

Extr. No.	Ingot No.	Billet Size (Dia.x Length) (inches)	Billet Weight (lb.)	* Glass	Extr. Temp (°F)	Extrusion Ratio	Max. Force (tons)	Min. Force (tons)	Peak "K" Factor	Extrusion Dimensions (inches)	Yield (%)	Remarks
898	VA72T	2.941 x 4.063	17.7	7810	3800	4.6:1	510	450	90,000	.892 x 1.847	72	Fr surface
899	VA73T	2.940 x 4.000	17.4	7900	4000	6.1:1	580	510	86,300	.693 x 1.818	77	Fr surface
900	VA74T	2.938 x 4.063	17.7	7900	4200	3.1:1	640	550	82,300	.537 x 1.710	80	Fr surface
911	VA70T	2.941 x 4.000	17.5	7810	3800	4.3:1	455	415	84,200	1.484 dia.	66	Gd surface
912	VA74B	2.950 x 4.000	17.6	7900	4000	4.3:1	430	380	79,800	1.481 dia.	66	Pr surface
913	VA73B	2.938 x 4.063	17.9	7900	4000	6.3:1	570	510	83,600	1.223 dia.	75	Fr surface
914	VA70B	2.939 x 4.000	17.0	7900	4200	4.1:1	No	Reading	------	1.493 dia.	70	Fr surface
915	VA72B	2.945 x 3.938	16.7	7900	4200	7.2:1	580	525	79,700	1.150 dia.	66	Pr surface
916	VA75B	2.940 x 4.063	17.6	7900	4200	6.2:1	570	510	84,800	1.235 dia.	75	Fr surface
917	VA76B	2.935 x 4.250	18.1	7900	4000	6.5:1	580	520	83,800	1.203 dia.	75	Fr, 120° die
926	VA71B	2.940 x 3.500	15.6	7900	4000	4.4:1	590	455	72,500	1.473 dia.	75	Pr surface
927	VA69B	2.940 x 4.500	19.7	7900	4000	4.3:1	530	380	99,000	1.490 dia.	65	Pr surface
928	VA71T	2.940 x 3.875	17.0	7900	4000	4.2:1	430	370	80,600	1.494 dia.	75	Pr surface
941	VA75T	2.937 x 4.000	17.5	7810	3800	4.5:1	550	450	99,800	.895 x 1.904	75	Pr surface (a)
942	VA75B	2.929 x 4.125	18.0	7900	4000	6.7:1	660	520	93,600	.613 x 1.884	75	Pr surface (a)
943	VA84T	2.937 x 6.625	28.5	7900	4000	4.2:1	500	400	94,300	1.499 dia.	75	Fr surface
1008	VA94	2.940 x 5.000	22.0	7900	3800	4.3:1	420	360	77,900	1.484 dia.	75	Fr surface
1009	VA95	2.940 x 5.000	22.0	7900	4000	4.2:1	430	390	81,700	1.505 dia.	66	Fr surface
1010	VA96	2.940 x 5.000	22.0	7900	3800	4.2:1	480	430	90,800	.954 x 1.915	55	Fr surface
1022	VA97	2.941 x 5.000	21.8	7900	3800	4.2:1	460	460	86,500	.938 x 1.932	72	Gd surface
1026	VA98	2.940 x 5.063	21.8	7900	3800	6.9:1	600	520	84,200	.600 x 1.880	65	Fr surface
1027	VA99	2.943 x 5.000	21.8	7810	4000	6.8:1	560	520	79,000	.605 x 1.890	65	Fr surface
1028	VA103	2.939 x 5.063	21.9	7900	4000	7.2:1	600	540	82,300	1.150 dia.	80	Gd surface
1042	VA106	2.852 x 5.063	20.8	7810	3600	5.3:1	570	485	92,200	1.337 dia.	56	Pr, Copper Jacket
1043	VA105	2.944 x 5.063	22.0	7900	3900	6.4:1	540	475	78,400	1.211 dia.	60	Fr surface
1045	VA109	2.855 x 5.000	20.6	7810	3650	6.6:1	580	440	83,300	1.200 dia.	75	Pr, Steel Jacket
1047	VA110	2.850 x 5.000	20.6	7810	3800	6.1:1	555	430	82,600	1.240 dia.	70	Pr, Steel Jacket
1073	VA107	2.940 x 5.937	22.0	None	3600	5.9:1	400	360	61,200	1.269 dia.	65	Pr, Mo Jacket
1074	VA108	2.940 x 6.125	22.4	None	3400	5.9:1	460	430	70,400	1.270 dia.	60	Pr, Mo Jacket

* Corning glass numbers

(a) Hot graphite (2800°F) nose and follower block
Billet end shape, 0.25" x 45° bevel
Nose block, 1018 steel coated with 8871 glass and heated to 1600°F
Follower block, machined graphite
Surfaces rated according to standard established in Figure 13

TABLE 10

TYPICAL MELTING RECORD OF W+6%Mo+2%Cb
(using 4-inch mold)

Heat number VA-99
Electrodes 01310-12 and 01310-14
Electrode size 1¾ x 39¾
Mold size 4 x 18"

Time (Min.)	Amperes	Volts	Pressure (Microns)	Stirring (Amperes)	Electrode Travel (Inches)
0	4000	28	.005	2	
½	4700	27	.03	2	
1	4800	28	.03	2	
2	5300	28	.03	2	
3	6300	28	.035	2	½
3½	6300	28	.03	4	2
6	6300	28	.023	4	4
7	6300	28	.03	3	5
9	6300	28	.03	2	7
14	6300	28	.026	2	14½
18	6300	28	.03	2	19
20	6300	28	.03	2	21
21	6300	28	.03	½	22
22½	6300	28	.04	½	24
23	4100	28	.02	½	25
23¼	3100	28	.02	½	25
23½	2500	28	.016	½	25
25½	Power Off	--	.024	-	--

TABLE 11

92W+6Mo+2Cb EXTRUSION HARDNESS

(Rockwell A)

Sample	Edge	Center	Edge
898 nose	72	72	71
898 center	72	72	72
898 tail	70	72	73
899 nose	72	72	72
899 center	71	71	71
899 tail	71	72	72
900 nose	68	67	71
900 center	70	70	71
900 tail	71.5	72	71.5
911 nose	70	70	71
911 center	70	70	70
911 tail	70	69	70
913 nose	70	69	72
913 center	72	70	72
913 tail	70	70	71
916 nose	71	71	71
916 center	71	70	72
916 tail	71	70	71
928 nose	71	70	70
928 center	70	70	71
928 tail	71	68	71

TABLE 12

TENSILE DATA ON 92W+6Mo+2Cb ALLOY

	913N	913C	915C	915T	928C	928T	Extruded and Swaged 1028	Extruded, Swaged, & Annealed 1028
0.2% Yield (psi)	33,800	27,400	33,000	33,300	30,600	33,100	46,700	9,600
0.5% Yield (psi)	35,600	29,000	34,900	35,600	33,000	34,500	47,700	11,600
Ultimate (psi)	39,300	33,620	39,330	39,300	37,080	38,120	48,200	17,200
Uniform Strain (%)	5.8	8.2	4.7	4.7	3.4	4.0	00.9	4.2
Fracture Stress (psi)	21,310	14,140	28,140	21,300	24,900	28,170	28,200	16,000
Fracture Strain (psi)	31.4	36.9	16.3	23.6	9.4	13.1	8.3	4.8
Original Hardness (Vicker 30Kg)	415	404	409	398	409	404	505	375
Final Hardness	406	406	400	396	415	404	467	368
Reduction of Area (%)	58.4	78.2	45.7	63.1	39.6	41.9	61.4	8.3
Elongation %	32.0	36.7	17.3	24.7	10.7	14.0	9.3	5.3
Peak Pressure (μ)	00.23	00.21	00.15	00.28	00.25	00.11	0.15	0.16

Specimens were maintained at 3000°F for 15 minutes before stress was applied.
Strain rate: 300 percent per hour
Tensile tests were conducted by Westinghouse Research and Deleopment Center, Churchill, Pa.

TABLE 13

RECRYSTALLIZATION BEHAVIOR OF W+0.6Cb

Showing Percent Recrystallization in As-Extruded Samples
Heated for 1 Hour at Indicated Temperature

Sample	As-Extruded	Percent Recrystallization 2800° F	3000° F	3200° F	3400° F
995 N	20	25	40	100	100
C	70	75	80	100	100
T	0	10	50	100	100
997 N	5	10	90	100	100
C	40	50	60	100	100
T	0	20	80	100	100
750 N	5	20	50	80	100
C	10	25	40	75	100
T	0	20	50	80	100
754 N	0	20	50	80	100
C	10	25	50	75	100
T	0	20	50	75	100
756 N	0	30	50	70	100
C	5	35	55	85	100
T	0	40	50	80	100
757 N	5	30	45	70	100
C	10	25	45	75	100
T	5	20	45	70	100
758 N	0	20	50	70	100
C	5	25	50	75	100
T	0	30	50	75	100
759 N	5	30	55	80	100
C	10	30	55	80	100
T	5	30	45	75	100
763 N	0	25	40	70	100
C	5	30	40	70	100
T	0	30	45	75	100

N, C, T - Nose, Center, Tail Samples

TABLE 14

EFFECT OF REDUCTION ON W+0.6Cb HARDNESS
(Forging and Rolling)

Rockwell A Hardness of Forged W+0.6Cb
(Average of 3 Readings)

Sample	Orig. Hardness (Annealed)	Forge Temp. (°F)	Hardness at Percent Reduction 20%	40%	60%	80%
761	70.3	2600	71.0	71.0	72.3	72.7
763	71.0	2000	70.7	70.3	71.0	73.3
763	71.7	2400	71.0	70.7	71.0	72.0
993	70.0	1600	71.7	72.0	72.0	73.3
993	71.0	2400	71.0	70.0	70.7	72.0

Rockwell A Hardness of Rolled W+0.6Cb
(Average of 3 Readings)

Sample	Orig. Hardness (Annealed)	Rolling Temp. (°F)	Hardness at Percent Reduction 20%	40%	60%	80%
759	71.0	1600	71.0	----	----	----
759	70.7	2000	71.3	71.7	72.0	----
759	71.0	2400	70.7	71.0	72.3	72.7
761	72.0	2000	72.0	72.3	----	----
763	71.3	2400	71.7	----	----	----
992	70.7	2000	71.3	----	----	----
993	70.0	2400	71.0	71.3	----	----

TABLE 15

HARDNESS (Rockwell A) OF EXTRUDED AND ANNEALED 92W+6Mo+2Cb

		Annealing Temperature																	
		2600° F			2800° F			3000° F			3200° F			3400° F			3600° F		
Sample		E	C	E	E	C	E	E	C	E	E	C	E	E	C	E	E	C	E
898	N	70	71	70	66	68	69	71	70	71	70	68	69	69	68	68	65	64	66
	C	67	71	71	70	70	71	70	71	71	66	67	67	65	65	67	67	67	68
	T	68	69	70	67	69	70	71	71	71	65	66	66	66	67	68	64	67	63
899	N	71	68	70	70	69	70	68	70	70	68	68	68	67	67	67	66	67	66
	C	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	T	68	67	79	71	70	71	68	70	70	69	70	68	67	67	68	63	63	63
900	N	70	69	70	68	70	70	68	70	68	69	68	68	67	68	68	65	67	66
	C	68	70	71	70	70	70	68	69	69	68	67	67	67	67	68	67	68	68
	T	69	71	71	71	68	70	69	69	70	66	67	68	67	68	68	65	65	67

N, C, T - Nose, Center, Tail samples

E, C, E - Edge, Center, Edge locations across sample surface.

TABLE 16

RECRYSTALLIZATION BEHAVIOR OF 92W+6Mo+2Cb ALLOY

Showing Percent Recrystallization in As-Extruded Samples Heated for 1 Hour at Indicated Temperature

		Percent	Recrystallization			
Sample	Extruded	2600°F	2800°F	3000°F	3200°F	3400°F
898 N	10	10	25	40	90	100
C	20	20	30	40	90	100
T	0	10	25	40	90	100
899 N	15	15	20	40	90	100
C	40	40	50	60	100	100
T	0	10	25	40	90	100
900 N	15	15	20	50	95	100
C	40	40	45	50	100	100
T	5	10	25	50	95	100

N, C, T - Nose, Center, Tail Samples

TABLE 17

TENSILE DATA ON SWAGED W+0.6Cb ALLOY

Extr. No.	Ingot No.	Stress .2% Y.P. (psi)	Stress .5% Y.P. (psi)	Ultimate Stress (psi)	Uniform Strain (%)	Fracture Stress (psi)	Fracture Strain (%)	Reduction of Area (%)	Measured Elongation (%)	Highest Test Pressure (microns)
935 (3)	VA-78	41,400	42,500	42,700	0.65	10,940	12.4	84.2	13.3	----
936 (3)	VA-79	43,500	44,800	45,000	0.70	11,470	13.3	89.1	14.0	----
956 (3)	VA-86	41,900	43,340	43,340	0.50	8,400	11.7	93.3	12.7	0.16
974 (3)	VA-92	31,200	32,600	32,700	0.40	16,000	6.0	42.0	6.7	0.10
994 a	31202	41,700	42,600	42,740	0.60	21,300	10.4	56.4	11.3	0.14
995 b	31192B	37,000	38,200	38,200	0.50	13,800	13.1	80.5	14.0	0.13
995 c	31192B	37,100	37,800	37,800	0.50	13,100	14.6	82.3	15.3	0.14
997 c	OM1523-3	44,600	45,900	46,200	0.70	25,400	11.6	58.3	12.7	0.16
750 d	KC1136B	43,600	46,200	46,600	0.60	4,700	9.6	9.7	9.3	----
750 e	KC1136B	40,500	42,000	42,000	0.70	41,000	0.9	14.4	---	----
763 f	KC1145A	39,200	41,200	41,800	0.90	29,000	5.0	45.9	5.0	----
763 g	KC1145A	53,600	56,500	58,100	0.80	16,500	8.7	71.2	7.2	----
632 (10)h	KC1072	54,000	54,900	55,070	0.70	21,700	6.6	90.8	7.2	0.12
632 (10)i	KC1072	57,800	59,400	59,640	0.70	17,970	7.1	87.1	7.2	0.18
632 (10)j	KC1072	57,300	58,500	58,790	0.70	16,000	6.6	86.0	6.4	0.13
632 (10)k	KC1072	61,500	62,700	63,310	0.70	27,780	6.0	74.4	6.4	0.15

Specimens were maintained at 3000°F for 15 minutes before stress was applied. Strain Rate: 300% per hour.

Numbers in ( ) indicate references on page 31.

a - Swaged to .840" dia. @ 2400°F, annealed 1 hour @ 3100°F, swaged to .690" dia. @ 2200°F (37% reduction)

b - Swaged to .940" dia. @ 2700°F, annealed 1 hour @ 3200°F, swaged to .610" dia. @ 2700°F (58% reduction)

c - Same as "b", except swaged to .610" @ 2400°F.

d-g - Annealed 1 hour @ 3600°F, reduced by forging as follows:
(d) 20% @ 2000°F, (e) 40% @ 2000°F, (f) 20% @ 2400°F, (g) 60% @ 2400°F.

h-k - Annealed 1 hour @ 3400°F, reduced by forging @ 2675°F as follows: (h) 47%, (i) 52%, (j) 40%, (k) 54%.

Tensile tests conducted by Westinghouse Research and Development Center, Churchill, Pa.

TABLE 18

BENDIX Cr+MgO EXTRUSION DATA

Billet Composition, 93.5% Cr+0.5%Ti+6%MgO
Unless Indicated Otherwise

*Indicates Rectangular Extrusions

Ext. No.	Bendix Billet No.	Density (%)	Ratio	Temp. (^oF)	Max. Force (Tons)	Min. Force (Tons)	Peak K Factor (psi)	Comments
808	442	84.4	*11.7:1	2400	340	280	37,000	Gd Surface
809	444	83.8	*12.1:1	2400	390	310	42,000	Gd Surface
810	430	85.2	*11.7:1	2300	390	310	43,000	Gd Surface
811	431	84.7	*12.1:1	2200	435	390	47,500	Gd Surface
829	455	83.8	*9.2:1	2000	580	550	70,500	Gd Surface
830	456	82.8	*8.1:1	2000	590	540	77,000	Gd Surface
831	457	83.4	*8:1	2000	620	540	80,500	Gd Surface
832	458	83.4	*8:1	2000	580	540	75,500	Gd Surface
833	459	83.4	*8:1	2000	590	540	76,500	Gd Surface
834	460	82.9	*8:1	2000	590	530	76,500	Gd Surface
844	481	82.1	*8.4:1	2000	590	530	75,000	Gd Surface
845	482	83.5	*8:1	2000	600	540	78,000	Gd Surface
846	483	82.9	*8:1	2000	580	525	75,500	Gd Surface
847	484	82.9	*7.8:1	2000	580	530	75,000	Gd Surface
849	485	84.0	*8.6:1	2000	600	570	75,500	Gd Surface
850	486	84.2	*8.7:1	2000	600	590	75,500	Gd Surface
851	487	85.0	*7.8:1	2000	600	540	79,000	Gd Surface
852	488	85.4	*7.8:1	2000	600	560	79,000	Gd Surface
853	489	86.6	*7.7:1	2000	620	580	81,500	Gd Surface
854	490	84.6	*7.4:1	2000	610	570	82,500	Gd Surface
855	491	85.6	*8.5:1	2000	610	530	77,000	Gd Surface
856	492	85.6	*8.3:1	2000	620	560	79,500	Gd Surface
857	493	86.5	*8.3:1	2000	610	540	78,500	Gd Surface
858	494	86.5	*8.3:1	2000	590	530	75,500	Gd Surface

TABLE 18 (continued)

BENDIX Cr+MgO EXTRUSION DATA

Ext. No.	Bendix Billet No.	Density (%)	Ratio	Temp. (^oF)	Max. Force (Tons)	Min. Force (Tons)	Peak K Factor (psi)	Comments
859	495	84.4	*8.3:1	2000	590	570	75,500	Gd Surface
860	496	86.5	*7.8:1	2000	600	540	79,000	Gd Surface
861	506	86.6	*7.7:1	2000	600	520	79,000	Gd Surface
862	507	88.4	*7.7:1	2000	NR	NR	------	Gd Surface
863	508	87.4	*8.8:1	2000	610	570	76,000	Gd Surface (Uncoated Die)
866	512	82.9	8.2:1	2200	630	NR	80,000	Gd Surface (Trouble Getting Billet In Container)
867	513	82.6	------	2300	---	---	------	Stuck
868	497	83.5	8.2:1	2000	575	480	73,500	Gd Surface (Uncoated Die)
869	498	84.2	8.2:1	2000	670	610	85,000	Fr Surface (Uncoated Die)
870	499	85.4	8.1:1	2000	610	480	78,000	Gd Surface (Uncoated Die)
871	500	84.4	8.1:1	2000	610	450	78,000	Gd Surface (Uncoated Die)
872	513	82.7	------	2450	660	500	------	Very Badly Cracked (Uncoated Die)
883	521	83.5	9.3:1	2500	580	530	70,500	Pr Surface (Fir Tree Effect)
884	515	77.0	9.3:1	2500	370	330	45,000	Gd Surface
885	516	77.3	9.3:1	2500	370	330	45,000	Gd Surface
886	522	79.0	------	2700	660	570	------	Fir Tree Effect (Entire Surface)
887	502	82.9	*9.1:1	2000	560	495	69,000	Gd Surface
888	503	82.8	*9.1:1	2000	560	480	69,000	Gd Surface
889	504	84.6	*9.1:1	2000	570	490	70,000	Gd Surface
890	505	82.8	*9.1:1	2000	545	440	67,000	Gd Surface

TABLE 18 (continued)

BENDIX Cr+MgO EXTRUSION DATA

Ext. No.	Bendix Billet No.	Density (%)	Ratio	Temp. (°F)	Max. Force (Tons)	Min. Force (Tons)	Peak K Factor (psi)	Comments
897	540	77.9	*9.2:1	2500	550	350	67,500	Gd Surface
902	532	81.5	*9.4:1	2000	510	400	61,500	Gd Surface
903	533	81.5	*9.4:1	2000	420	380	51,000	Gd Surface
904	534	81.2	*9.4:1	2000	500	430	60,000	Gd Surface
905	535	81.6	*9.2:1	2000	540	460	66,000	Gd Surface
906	537	83.8	*9.2:1	2000	580	460	70,500	Gd Surface
907	538	83.0	*8.5:1	2000	510	400	64,500	Gd Surface
908	539	82.9	*8.5:1	2000	560	500	70,500	Gd Surface
920	554	----	10:1	2200	455	450	53,000	Gd Surface
921	555	----	10:1	2200	435	435	51,000	Gd Surface
922	557	----	10:1	2200	395	370	46,000	Gd Surface
923	558	----	10:1	2200	390	380	46,000	Gd Surface
924	552	----	10:1	2200	400	380	46,000	Gd Surface
925	553	----	10:1	2200	380	380	45,000	Gd Surface
944	---	----	10:1	2200	440	410	52,000	Gd Surface
945	---	----	10:1	2200	440	410	52,000	Gd Surface
1013	542	85.4	*9.6:1	2200	410	340	47,000	Gd Surface
1014	543 100Cr	77.9	*9.6:1	2200	400	320	45,000	Gd Surface
1015	544	81.0	*9.6:1	2200	400	360	45,000	Gd Surface
1016	547 Cr+9MgO	81.3	*9.6:1	2200	400	360	45,000	Gd Surface
1017	564 Cr+8ThO_2	87.6	*9.6:1	2200	420	360	49,000	Gd Surface
1018	566 100Cr	----	*9.6:1	2200	420	360	49,000	Gd Surface
1019	567 Cr+3MgO	81.3	*9.6:1	2200	400	340	45,000	Gd Surface
1020	568	81.6	*9.6:1	2200	400	360	45,000	Gd Surface
1021	569	70.4	*9.6:1	2200	400	340	45,000	Gd Surface

TABLE 18 (continued)

BENDIX Cr+MgO EXTRUSION DATA

Ext. No.	Bendix Billet No.	Density (%)	Ratio	Temp. (°F)	Max. Force (Tons)	Min. Force (Tons)	Peak K Factor (psi)	Comments
1067	570 $Cr+6MgCr_2O_4$	78.7	*10.0:1	2200	560	430	66,080	Gd Surface
1068	575 Cr+5MgO	79.3	*10.0:1	2200	535	355	63,130	Gd Surface
1069	576 Cr+4MgO	81.0	*10.0:1	2200	555	355	65,490	Gd Surface
1070	577 Cr+2MgO	79.0	*10.0:1	2200	550	360	64,900	Gd Surface
1071	578 Cr+1MgO	79.1	*10.0:1	2200	545	355	64,310	Gd Surface
1072	574	77.9	*8.0:1	2500	525	445	61,950	Gd Surface (Some Temperature Loss)

TABLE 19

MISCELLANEOUS MOLYBDENUM ALLOYS

Extr. No.	Agency	Billet Composition	Billet Condition	Ratio	Glass	Temp (°F)	Max Force (Tons)	Min Force (Tons)	Peak K Factor (PSI)	Comments
848	W	Mo+25W+.1Zr	AC	7.5:1	7900	4000	500	410	67,000	Good Surface
910	M	Mo+.5Ti	(1)	7.7:1	0010	2200	540	320	71,000	Extrusion Cracked
985	AEC	Molybdenum	HR	8.8:1	7810	3200	440	400	55,000	Tubing, Gd Surface
986	AEC	Molybdenum	HR	8.8:1	7810	3000	550	480	69,000	Tubing, VG Surface
991	CM	Mo+.26Zr+.04C	AC	6:1	7900	3800	480	400	74,000	Temp & Friction Study
1023	GE	Mo+1Zr+.1C	AC	10:1	7900	3650	610	510	71,980	Fair Surface
1024	GE	Mo+1.25Ti+.5Zr +.1C	AC	4.3:1	7900	3500	470	430	89,000	Fair Surface
1025	GE	Mo+1.25Ti+.5Zr +.1C	AC	4.3:1	7900	3500	460	420	89,000	Fair Surface
1029	CM	Mo+0.05C+1.5Cb +0.5Ti+0.3Zr	AC	4:1	7740	3000	495	425	91,500	Fair to Gd Surface
1030	CM	Mo+0.10C+1.25Ti +0.3Zr	AC	4.2:1	7740	2800	505	430	93,500	Good Surface
1032	CM	Mo+0.1Be+0.003C	AC	4.2:1	7740	3000	480	300	90,800	Good Surface Jacketed
1035	CM	Mo+0.05C+1.5Cb +0.5Ti+0.3Zr	AC	4:1	7052	2600	610	510	119,000	Good Surface
1036	CM	Mo+0.10C+1.25Ti +0.3Zr	AC	6:1	7052	2800	650	645	98,300	Stuck
1037	CM	Mo+0.10C+1.25Ti +0.3Zr	AC	4:1	7052	2800	565	490	110,000	Good Surface
1038	CM	Mo+0.10C+1.25Ti +0.3Zr	AC	4:1	7052	2800	540	490	110,000	Good Surface
1039	CM	Mo+0.05C+1.5Cb +0.5Ti+0.3Zr	AC	4:1	7052	2800	570	500	111,000	Good Surface
1040	CM	Mo+0.05C+1.5Cb +0.5Ti+0.3Zr	AC	4:1	7052	2800	565	500	113,200	Good Surface
1041	CM	Mo+0.05C+1.5Cb +0.5Ti+0.3Zr	AC	4:1	7052	2800	570	505	114,000	Good Surface
1046	CM	Mo+0.10C+1.25Ti +0.3Zr	AC	6:1	7052	2800	700	---	------	Stuck
1054	AEC	Molybdenum	HR	8.8:1	None	3000	600	530	75,000	Tubing, Gd Surface
1055	AEC	Mo+.5%Ti	HR	8.8:1	None	3500	510	415	63,800	Tubing, Gd Surface
1056	AEC	Mo+0.5Ti+0.08Zr	HR	8.8:1	None	3750	520	340	64,900	Tubing, Fr Surface
1057	AEC	Mo+0.5Ti	HR	8.8:1	None	3500	500	370	62,400	Tubing, Fr Surface
1058	AEC	Mo+0.5Ti	HR	8.8:1	None	3500	535	420	66,800	Tubing, Fr Surface
1059	AEC	Mo+.5Ti+.08Zr	HR	8.8:1	None	3700	550	470	66,800	Tubing, Fr Surface
1060	AEC	Mo+.5Ti+.08Zr	HR	8.8:1	None	3700	No Reading		------	Tubing, Gd Surface

(1) Composite billet

Agency Code W = Westinghouse, M = Marquardt, AEC = Atomic Energy Commission, CM = Climax Molybdenum, GE = General Electric

Surfaces rated according to standard established in Figure 13.

TABLE 20

MISCELLANEOUS TUNGSTEN ALLOYS

Ext. No.	Agency	Billet Composition	Ratio	Glass	Temp. (°F)	Max. Force (Tons)	Min. Force (Tons)	Peak K Factor (psi)	Comments
812	C	W+.089Hf+.002C	4.2:1	7740	3600	410	360	77,000	Gd Surface (Mo Jacketed)
813	C	W+3.2Mo+.102Hf +.002C	4.2:1	7740	3600	410	345	77,000	Gd Surface (Mo Jacketed)
814	C	W+3.2Mo+.06Zr +.003C	4:1	7740	3600	410	345	80,500	Gd Surface (Mo Jacketed)
815	C	W+.99Cb+.06C	3:1	7900	4000	NR	NR	------	Gd Surface
864	WC	W	*6.2:1	7740	3400	465	400	68,000	Gd Surface
865	WC	W	*6:1	7741	3200	480	415	72,500	Gd Surface
873	C	W+1.0Cb+.002C	4.2:1	7810	3800	395	330	74,000	Very Gd Surface (Mo Jacketed)
874	C	W+3Mo+1Cb+ .002C	3.8:1	7810	3800	365	330	72,000	Gd Surface (Mo Jacketed)
875	C	W+.1Hf+.002C	6.5:1	7740	3600	460	430	67,500	Gd Surface (Mo Jacketed)
876	C	W+3Mo+1Cb +.002C	8.7:1	7810	3800	500	460	62,500	Gd Surface (Mo Jacketed)
877	C	W+3Mo+.1Hf +.002C	8.6:1	7740	3600	560	495	70,000	Gd Surface (Mo Jacketed)
878	C	W+.05Zr+.002C	9:1	7740	3600	560	495	68,500	Gd Surface (Mo Jacketed)
879	C	W+1.0Cb+.002C	8.4:1	7810	3800	495	460	63,000	Gd Surface (Mo Jacketed)
880	C	W+.1Hf+.002C	9:1	7740	3600	530	495	63,500	Gd Surface (Mo Jacketed)
881	C	W+3Mo+.1Hf +.002C	8.7:1	7740	3600	560	525	70,000	Gd Surface (Mo Jacketed)
882	C	W+.05Zr+.002C	9.2:1	7740	3600	560	525	68,500	Gd Surface (Mo Jacketed)
891	C	W+3Mo+.05Zr +.002C	9.1:1	7740	3600	545	480	67,000	Gd Surface (Mo Jacketed)
892	C	W+.05Zr+.01B	9.4:1	7740	3600	545	480	65,500	Gd Surface (Mo Jacketed)
893	C	W+3Mo+.05Zr +.002C	9.3:1	7740	3600	620	590	75,500	Gd Surface (Mo Jacketed)
894	C	W+.05Zr+.01B	9.2:1	7740	3600	570	540	69,500	Gd Surface (Mo Jacketed)
918	W	Sintered W, 88% dense	6.5:1	7900	4000	430	380	63,000	Fair Surface
975	W	Sintered W	6.5:1	7900	4000	500	450	73,000	Fair Surface
1011	W	Sintered W	6.5:1	7900	4000	530	430	78,000	Fair Surface
1031	C	W+.003C+3.0Mo +0.05Zr	4.2:1	7740	3400	400	360	73,400	Gd Surface (Mo Jacketed)
1033	C	W+.003C+3.0Mo +0.05Zr	6.5:1	7740	3200	530	430	76,900	Gd Surface (Mo Jacketed)
1034	C	W+.003C+3.0Mo +0.05Zr	6.4:1	7740	3100	590	520	87,000	Gd Surface (Mo Jacketed)
1064	L	W+60ppmC+20ppmO +.15Mo	4.2:1	7740	3200	390	335	72,000	Fair Surface

All billets from arc melted ingots except 918, 975, and 1011.

Agency Code WC = Wah Chang, C = Climax, W = Westinghouse, L = Ladish

Surfaces rated according to standard established in Figure 13.

TABLE 21

INTERNAL PROGRAM SUPPORT

Ext. No.	Billet Composition	Ratio	Temp. (°F)	Glass	Max. Force (Tons)	Min. Force (Tons)	Peak K Factor (psi)	Comments
848	Mo+25W	7.5:1	4000	7900	500	410	68,000	Press Demonstration
910	Mo+.5Ti (Steel Jacket)	7.7:1	2200	0010	540	---	-------	Material Cracked
937	Cb	9.2:1	3200	7740	No	Reading	------	Faulty Extrusion
938	Cb+5Mo	8.5:1	3200	7740	380	290	48,000	Gd Surface
939	Cb+5W	8.9:1	3000	7740	455	300	57,000	Fr Surface
940	Cb+5Mo+5W	8.5:1	3000	7740	560	460	67,000	Fr Surface
946	W+0.6Cb+.06Zr	6.5:1	3800	7810	530	470	77,000	Gd Surface
947	W+0.6Cb+.02Ti	6.5:1	3800	7810	495	470	72,600	Gd Surface
955	W+0.6Cb+.12Zr	6.5:1	3800	7810	570	520	83,500	
964	W+.6Cb+.12Zr +.04Ti	6.5:1	3800	7810	550	480	81,300	Fr Surface
965	W+0.6Cb	6.5:1	3800	7810	No	Reading	------	Fr Surface
991	Mo+.26Zr+.04C	6.3:1	3800	7900	480	---	71,000	Temp & Friction Studies, Die Tonnage-400
998	Cb+20W	10.5:1	3200	7740	460	320	53,000	Pr Surface
999	Cb+15W	8.9:1	3200	7740	540	320	68,500	Pr Surface

TABLE 21 (continued)

INTERNAL SUPPORT PROGRAM

Temperature and Friction Study Data

Extr.	Composition	Ratio	Lubricant	Temp. (°F)	Breakthrough Tonnage Stem	Breakthrough Tonnage Die
952	1018 steel	8:1	8871	1600	640	360
953	1018 steel	8:1	8871	1600	580	350
960	Copper	6.0:1	Graphite	800	540	240
961	Copper	6.0:1	None	1000	500	200
962	Copper	6:1	Graphite	800	540	240
963	1018 steel	6:1	Graphite	1600	540	340
967	Copper	6:1	Graphite	1200	450	175
968	Copper	6:1	None	800	450	310
969	1018 steel	6:1	Graphite	1600	460	340
970	1018 steel	6:1	Graphite	1600	540	330
971	1018 steel	6:1	Graphite	1600	470	280
972	1018 steel	6:1	0010	1800	340	240
976	1018 steel	6:1	None	1600	540	300
977	1018 steel	6:1	0010	1600	410	280
978	1018 steel	6:1	None	1800	350	260
979	1018 steel	6:1	0010	1800	430	260
980	1018 steel	6:1	None	1950	370	230
981	1018 steel	6:1	0010	1950	290	180
988	1018 steel	6:1	0010	1600	340	280
989	1018 steel	6:1	None	1950	340	240
990	1018 steel	6:1	None	1950	320	250
1000	1018 steel	6:1	None	1800	570	255
1001	1018 steel	6:1	None	1600	640	260
1002	1018 steel	6:1	None	1600	640	260
1003	1018 steel	6:1	0010	1600	640	NR
1004	1018 steel	6:1	0010	1600	500	260

TABLE 21 (continued)

INTERNAL SUPPORT PROGRAM

Temperature and **Friction** Study Data

Extr.	Composition	Ratio	Lubricant	Temp. (°F)	Breakthrough Tonnage Stem	Die
1005	1018 steel	6:1	Cu jacket	1600	260	260
1006	1018 steel	6:1	0010	1600	370	310
1007	1018 steel	6:1	0010	1600	360	280
1065	1018 steel	6:1	None	1600	590	210
1066	1018 steel	6:1	0010	1600	620	260

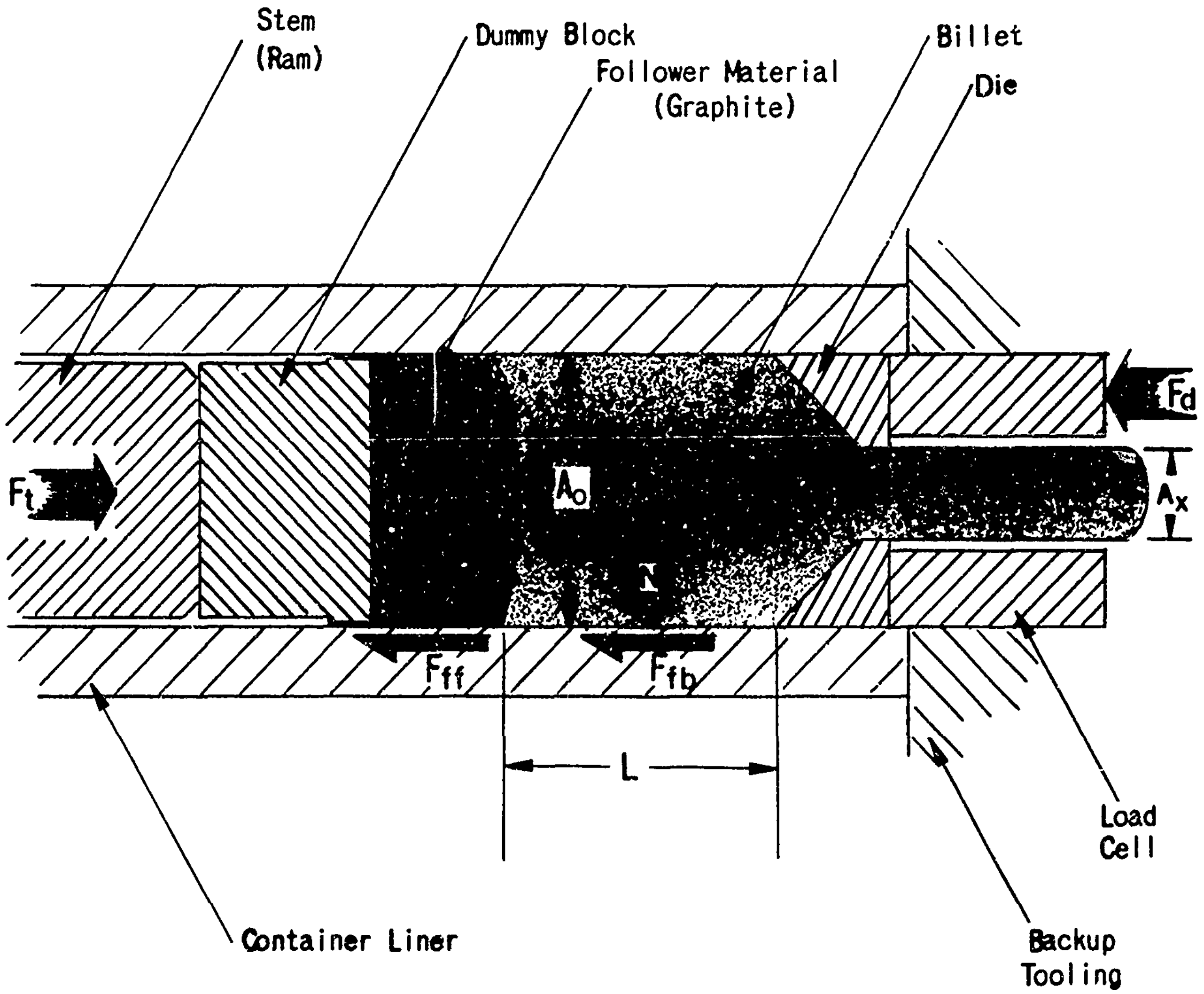


Figure 1 - Schematic Illustration of an Extrusion Process

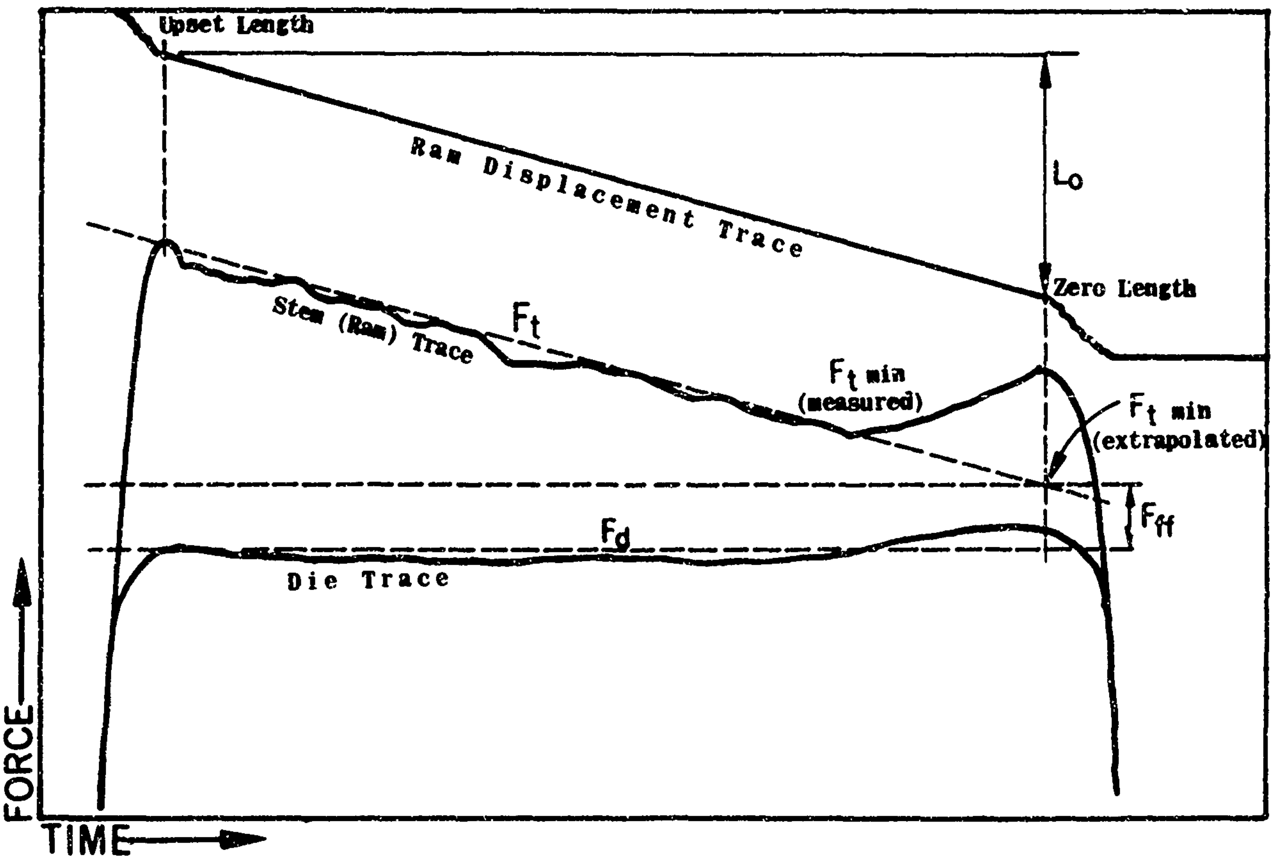


Figure 2 - Data Trace Schematic, Showing Distribution of Forces During Extrusion for Determination of Billet Friction.

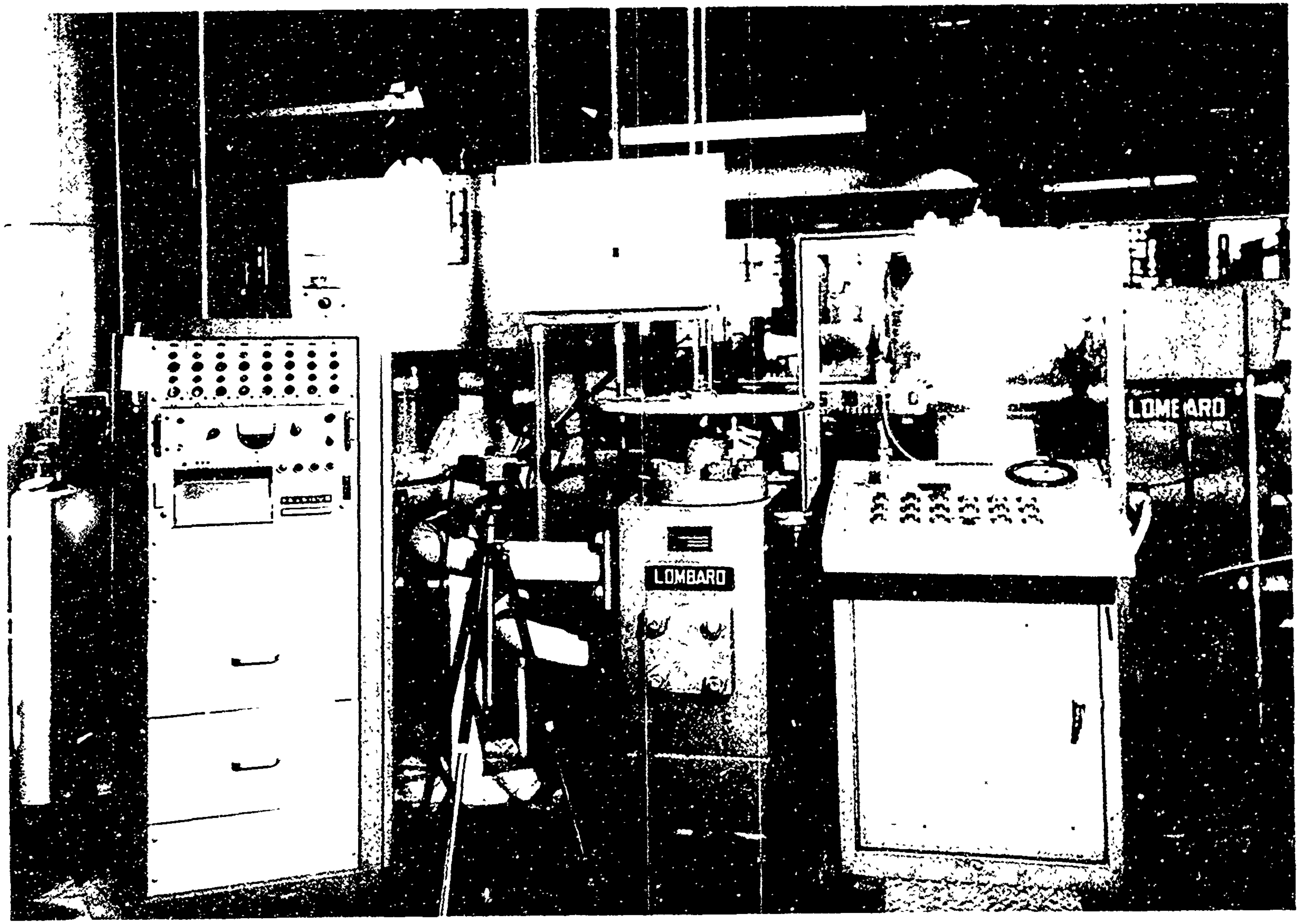


Figure 3 - Minneapolis Honeywell 1508 Visicorder (L). This Instrument Provides Data on Pressure, Speed, and Temperature During Extrusion. Temperature is Sensed by Instrument on Tripod.

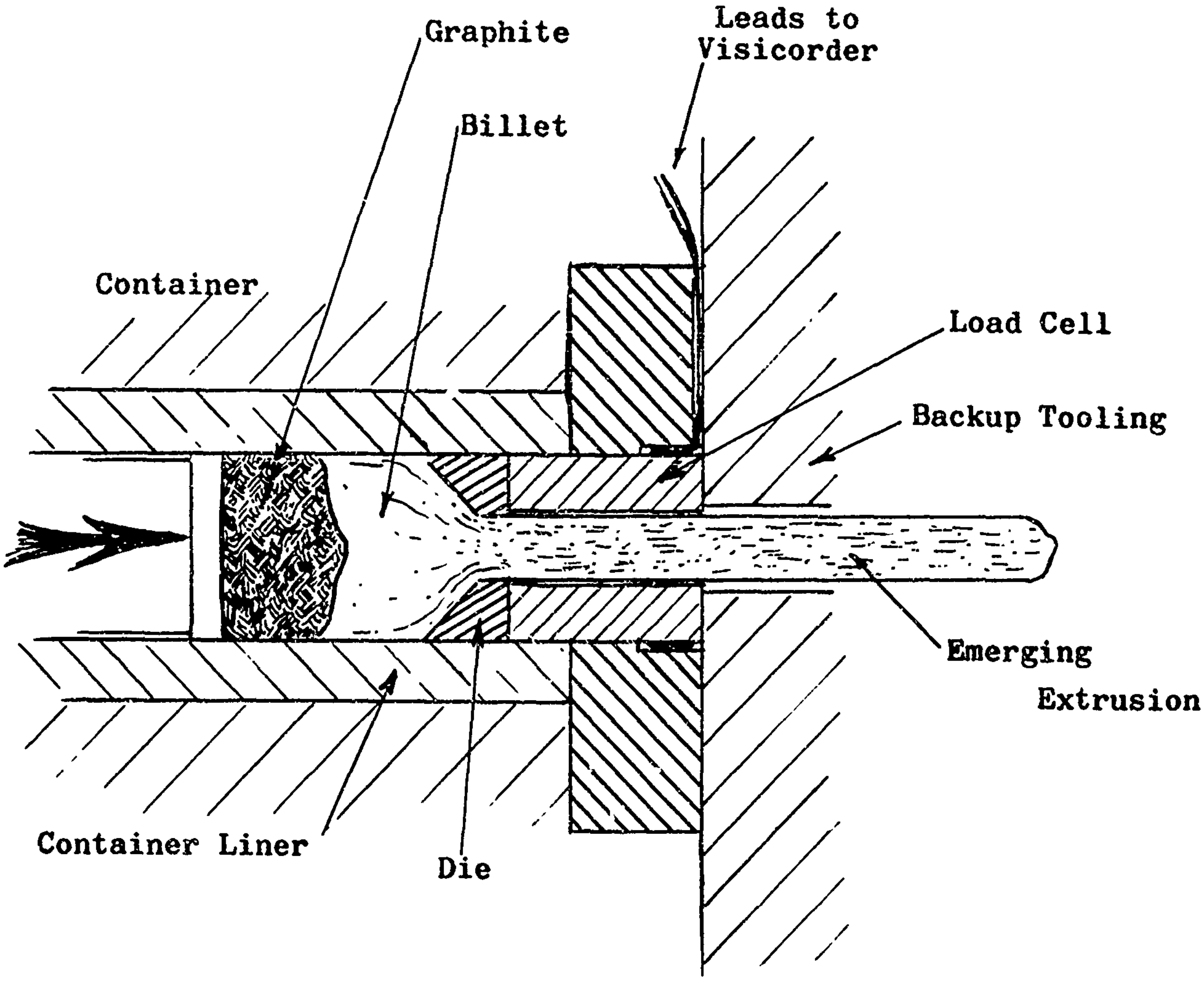


Figure 4 - System for Die Pressure Measurement. Force on Die is Transmitted Directly to Load Cell to Which Strain Gages are Attached, While Force on Container and Liner are Transmitted to Backup Tooling.

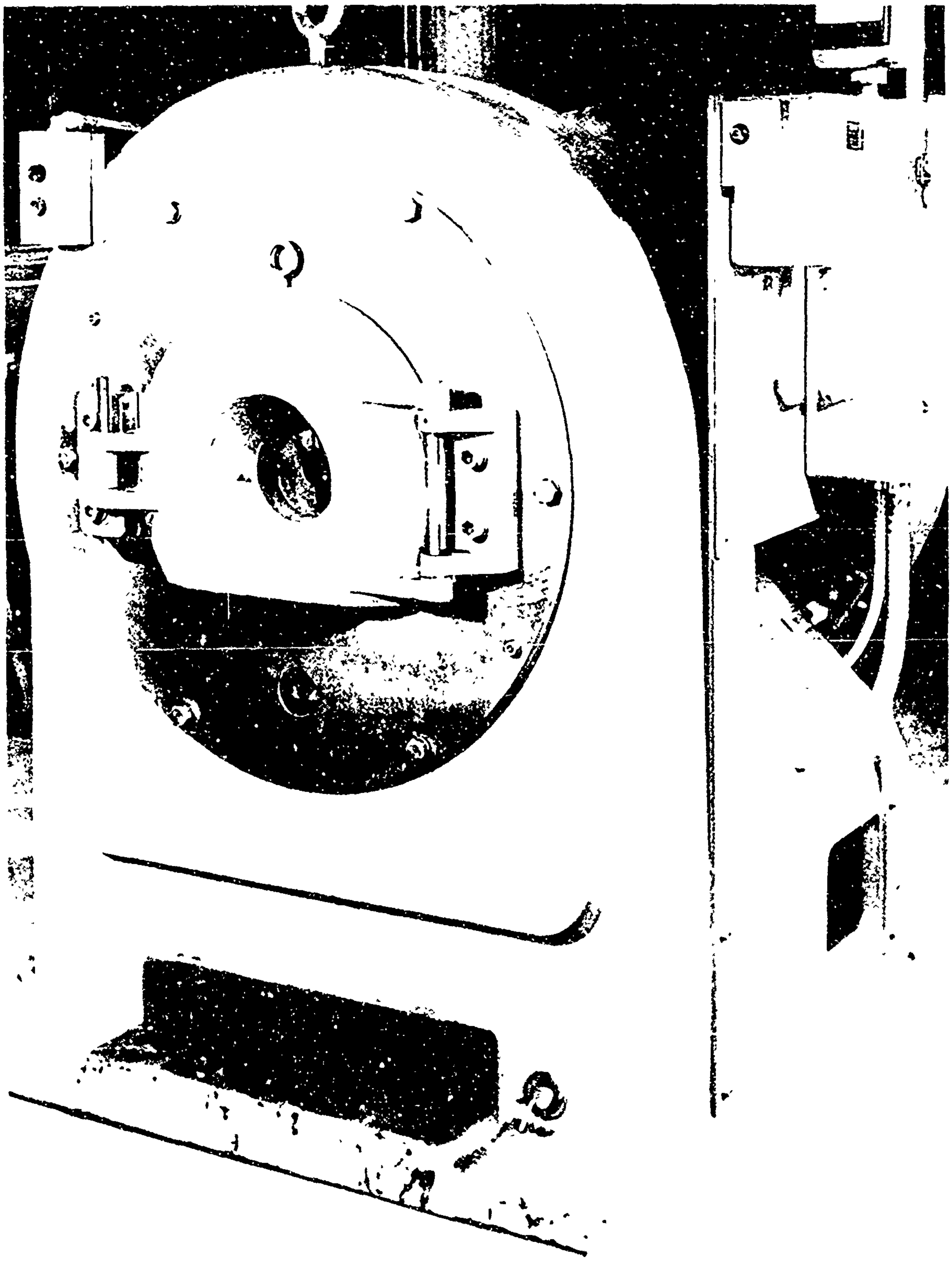


Figure 5 - Fenn Model 6F, 2-Die Swaging Machine.

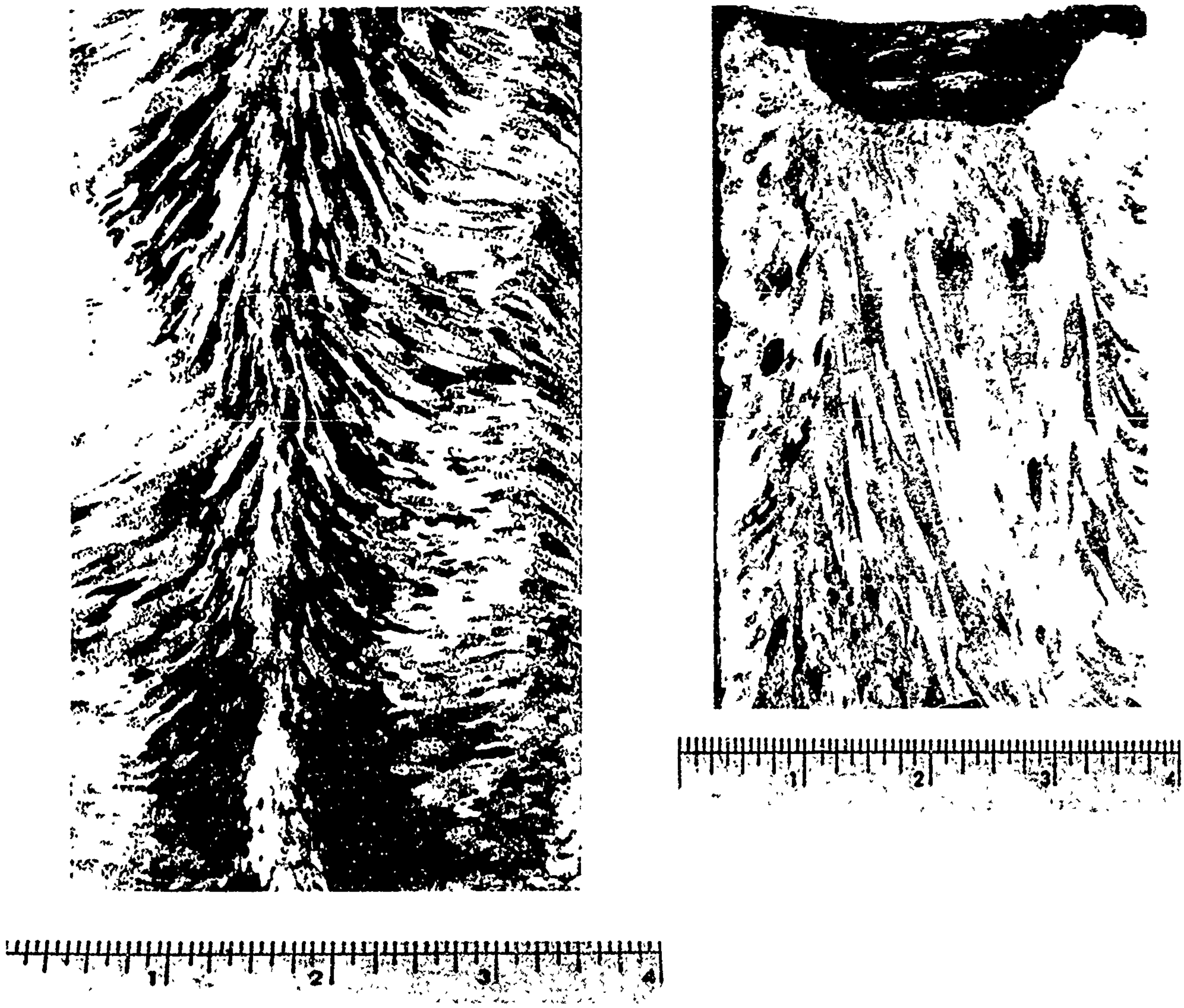


Figure 6 - W+0.6Cb Ingot Macrostructure. Ingot Produced by Oremet Using Alternating Current on Left, Ingot Produced at AFML Using Direct Current, Straight Polarity on Right.

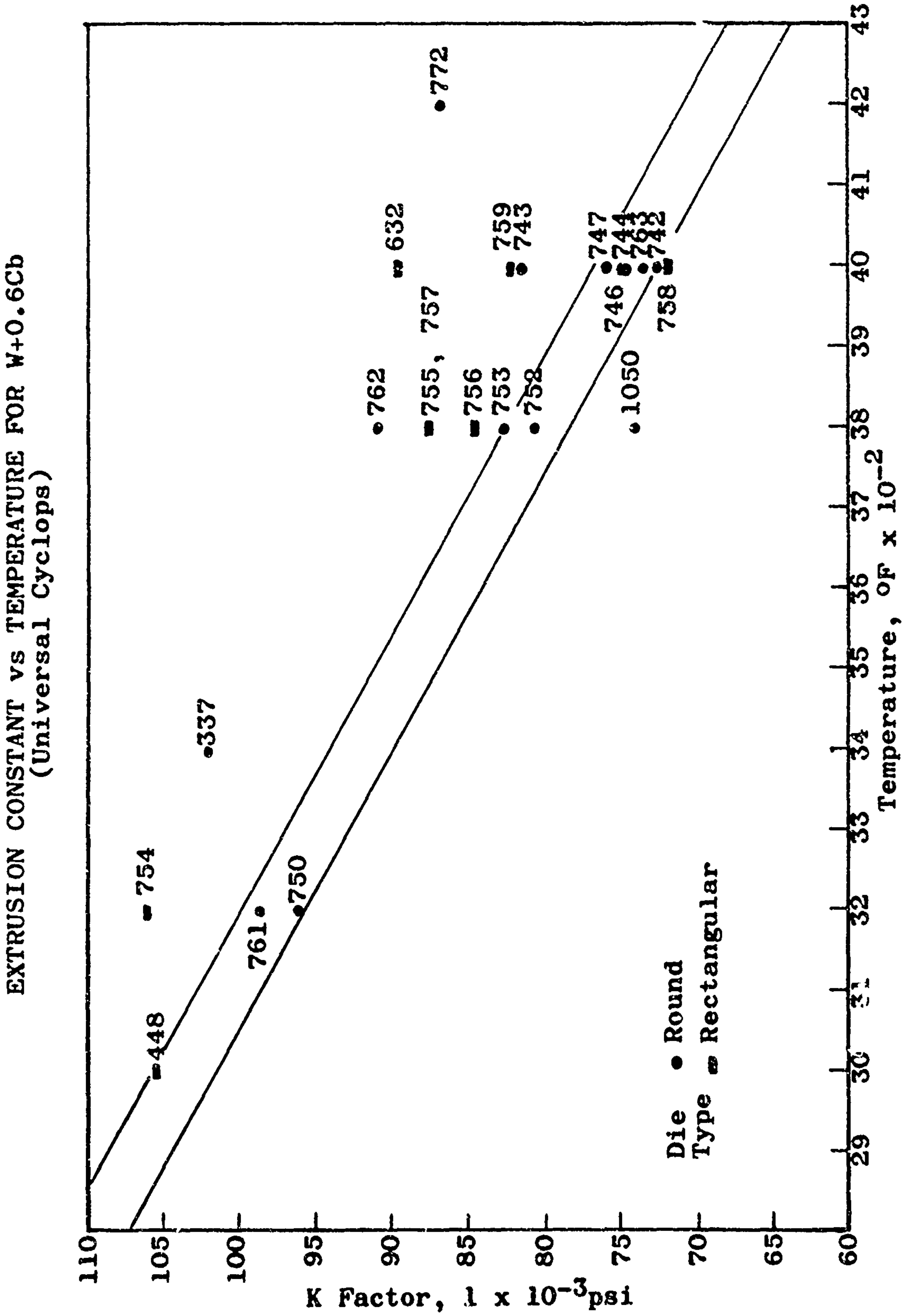


Figure 7 - Relation of Temperature and Extrusion Constant for Universal Cyclops W+0.6Cb.

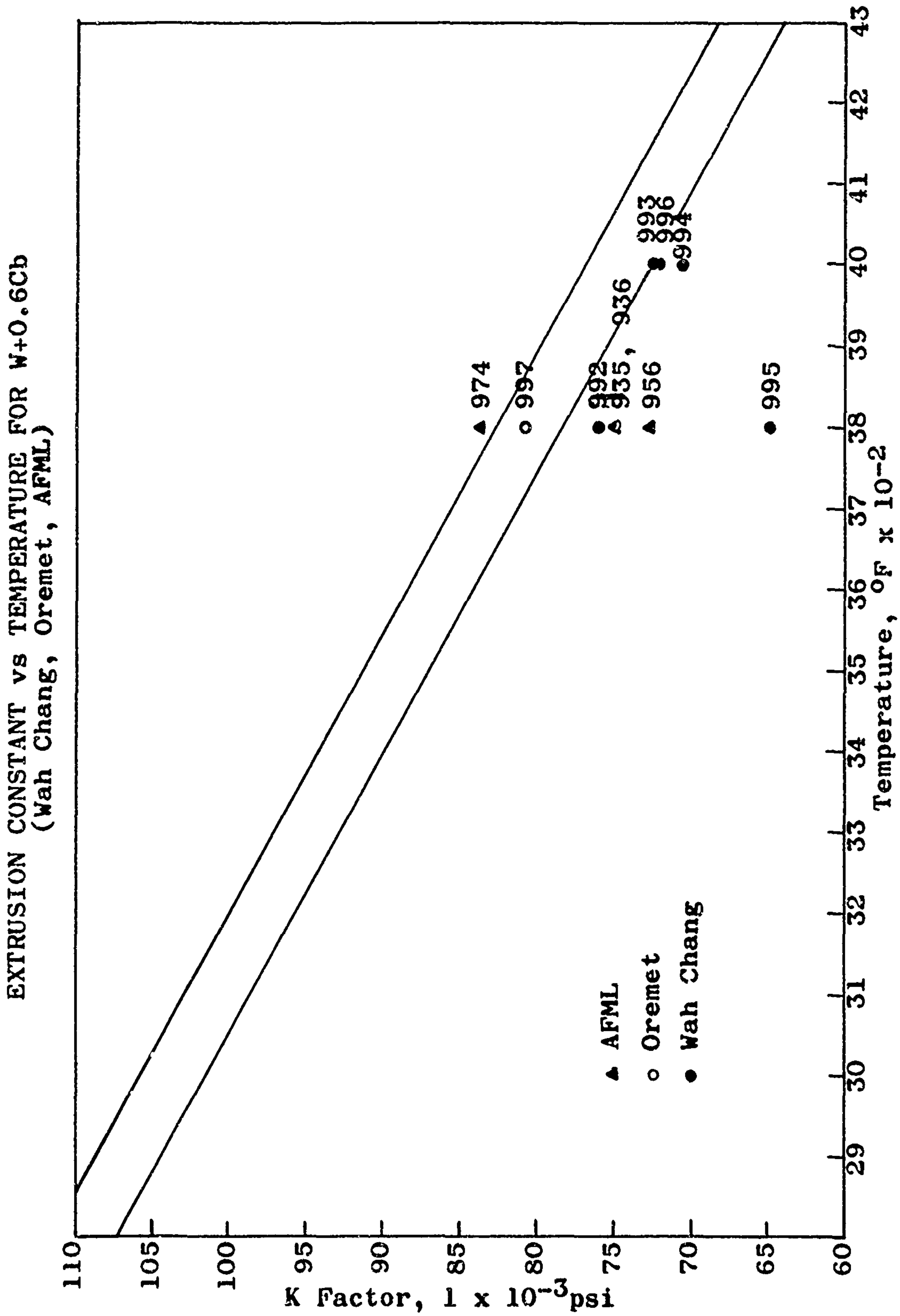
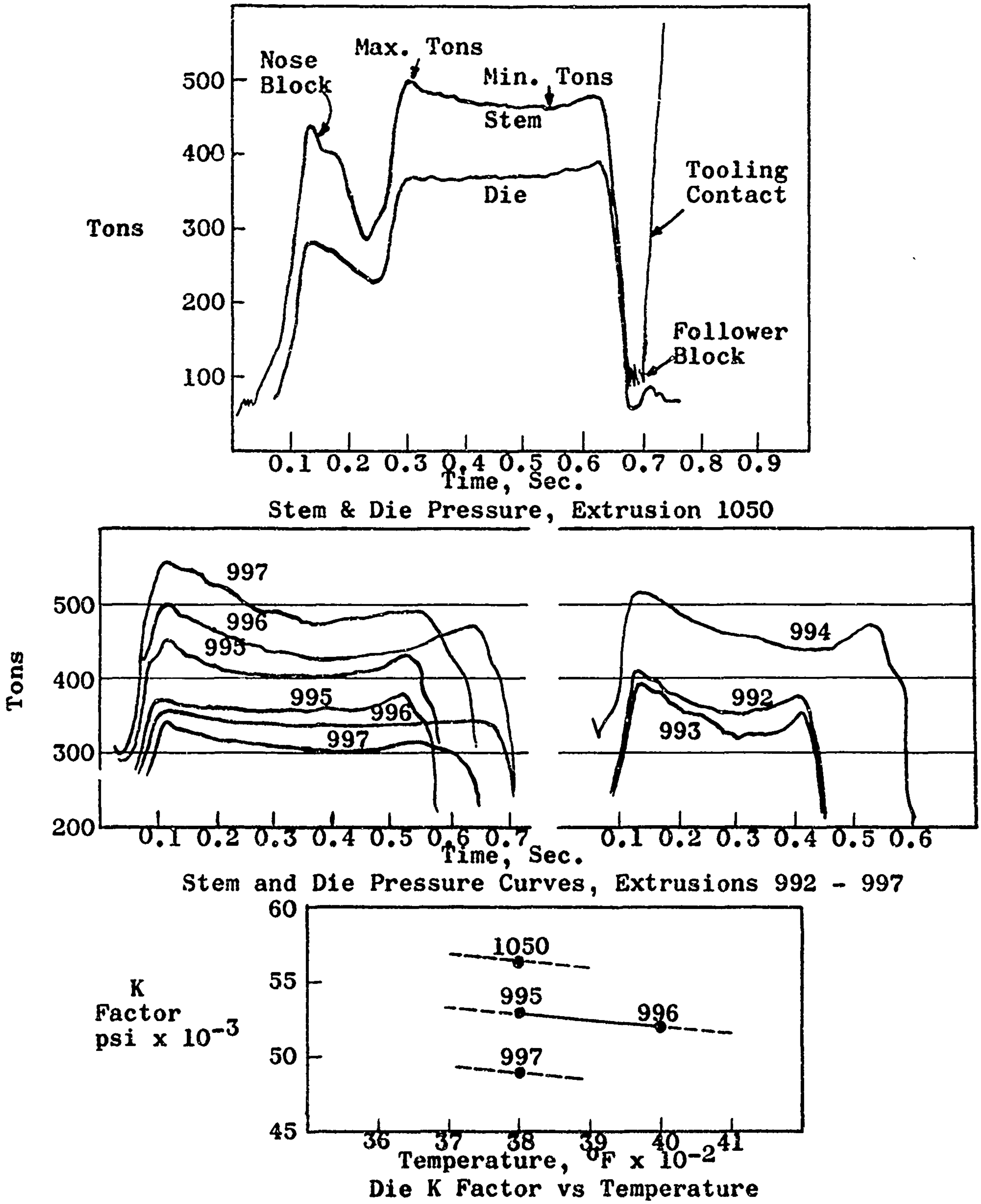


Figure 8 - Relation of Temperature and Extrusion Constant, Other W+0.6Cb Suppliers Plotted on Universal Cyclops K Factor Band.

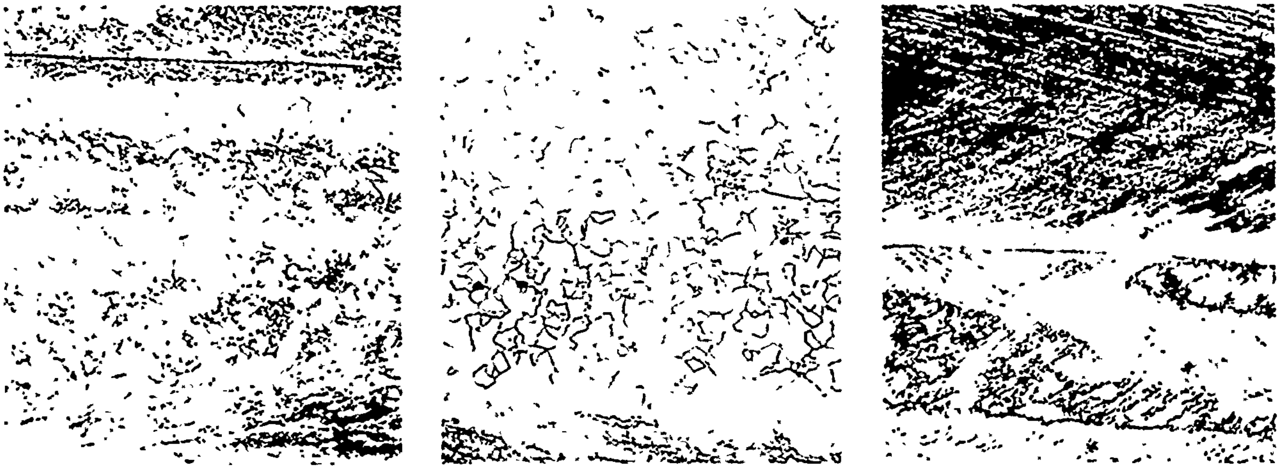


Stem & Die Pressure, Extrusion 1050

Stem and Die Pressure Curves, Extrusions 992 - 997

Die K Factor vs Temperature

Figure 9 - Stem and Die Loading vs Time and Die K Factor vs Temperature For W+0.6Cb Extrusions.

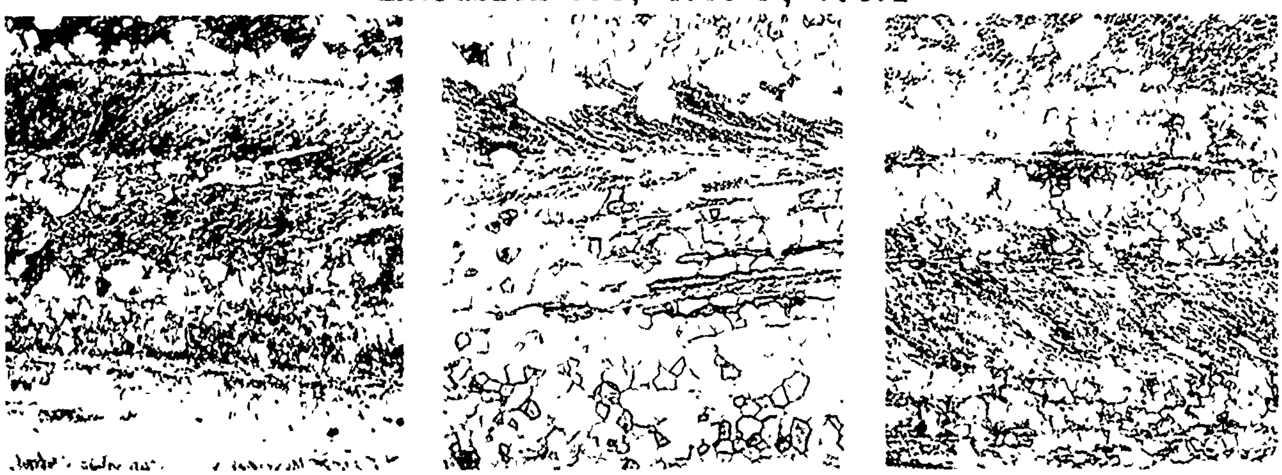


Nose Center Tail

Extrusion 993, 4000°F, 4.3:1

Nose Center Tail

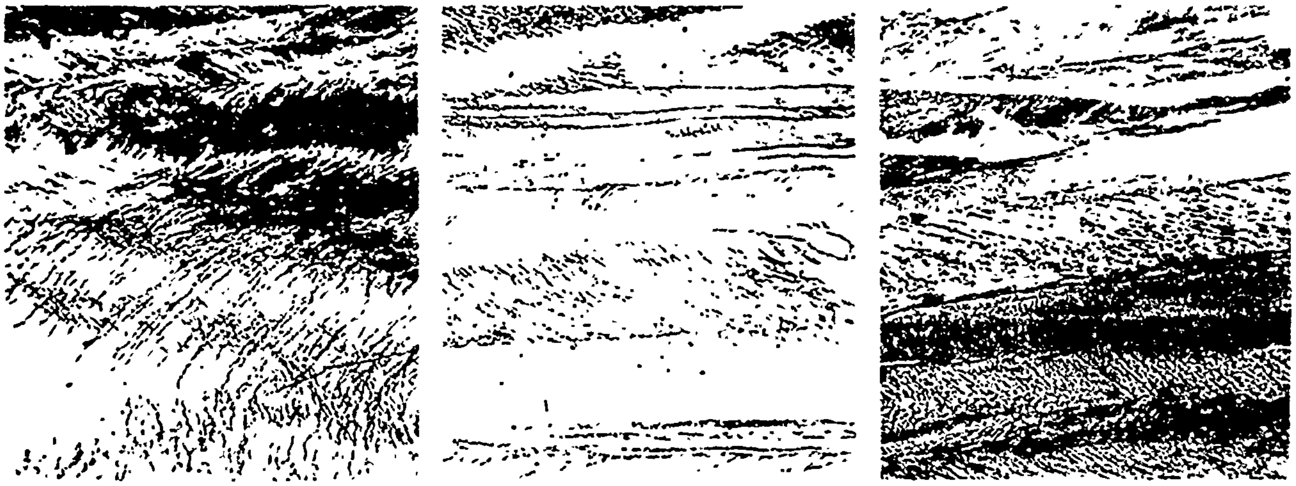
Extrusion 994, 4000°F, 7.4:1



Nose Center Tail

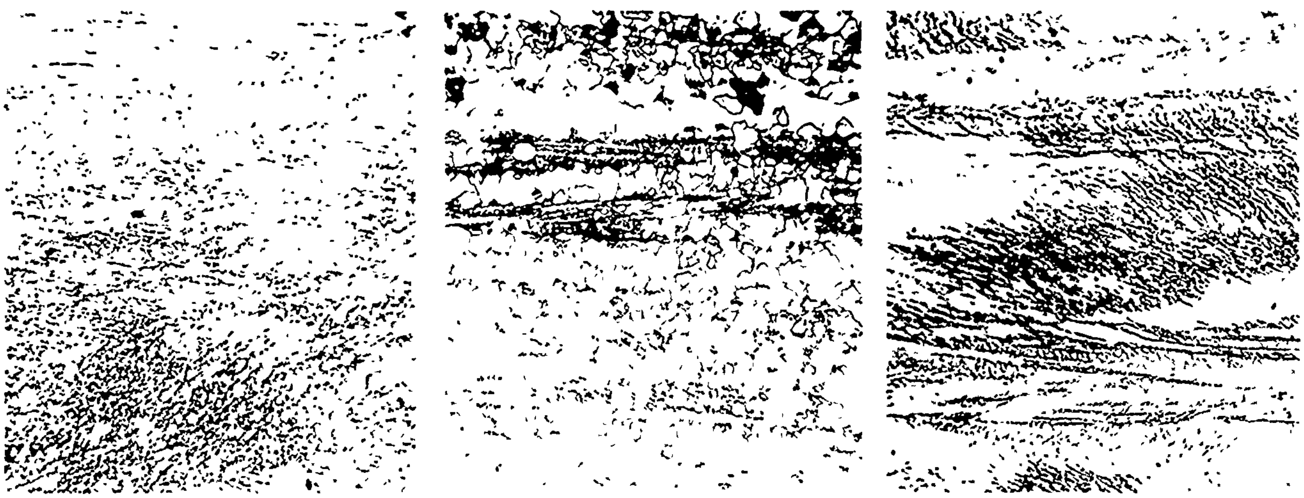
Extrusion 996, 4000°F, 6.4:1

Figure 10 - W+0.6Cb Extrusion Microstructures, from Wah Chang Billets.
Electropolished - Murakami's Etch - 50X



Nose Center Tail

Extrusion 761, 3200°F, 4.2:1



Nose Center Tail

Extrusion 763, 4000°F, 4.1:1

Figure 11 - W+0.6Cb Extrusion Structures from Universal Cyclops Billets, Showing Effect of Extrusion Temperature on Recrystallization.

Electropolished - Murakami's Etch - 50X

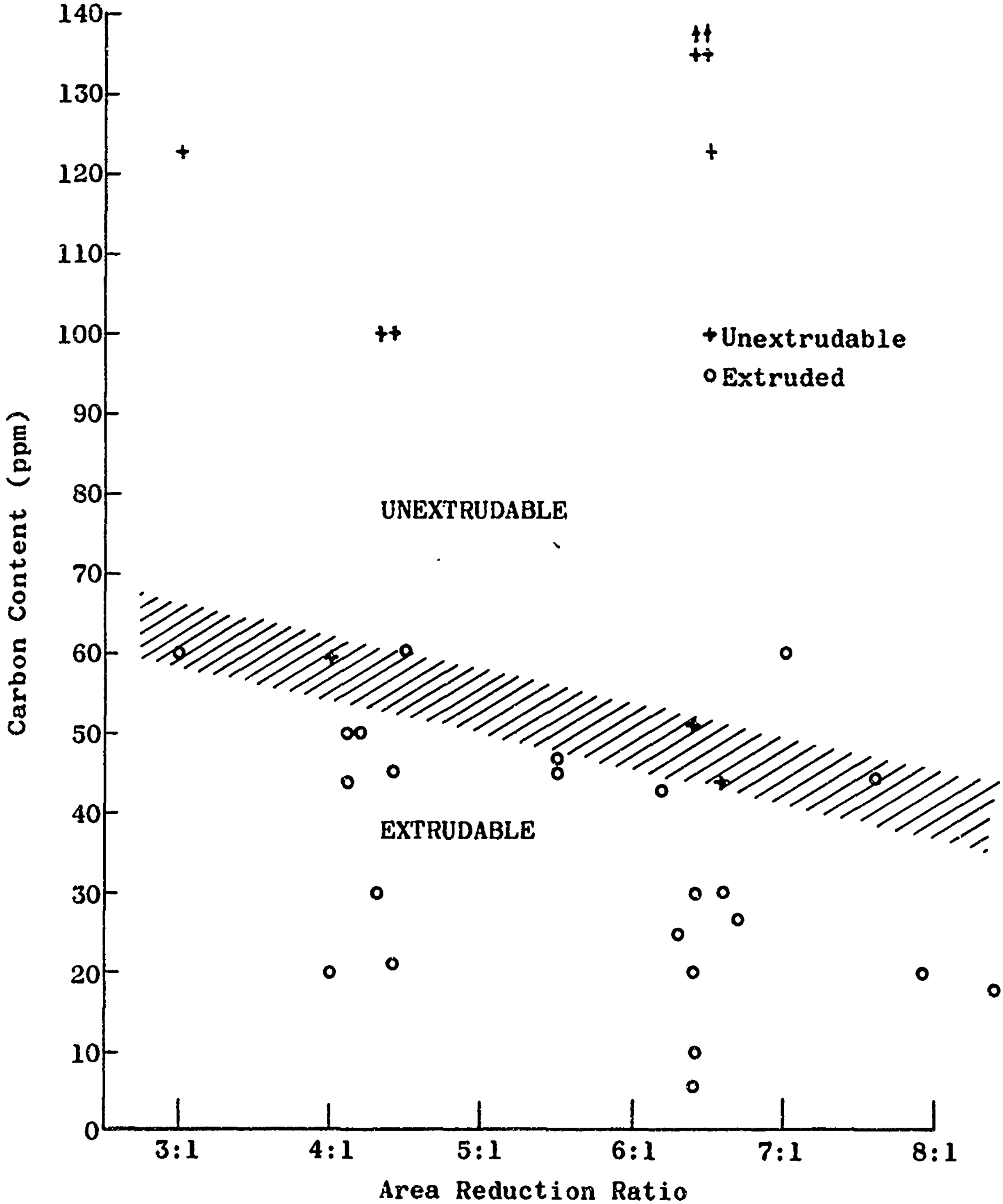
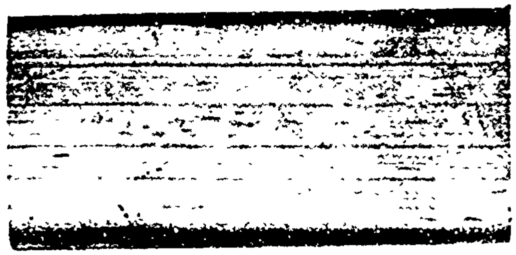


Figure 12 - Effect of Carbon Content on Extrudability at 3800 and 4000°F of W+0.6Cb Arc Cast Billets.



Very Good

Good

Fair

Poor

Figure 13 - Rating of Extruded Surfaces

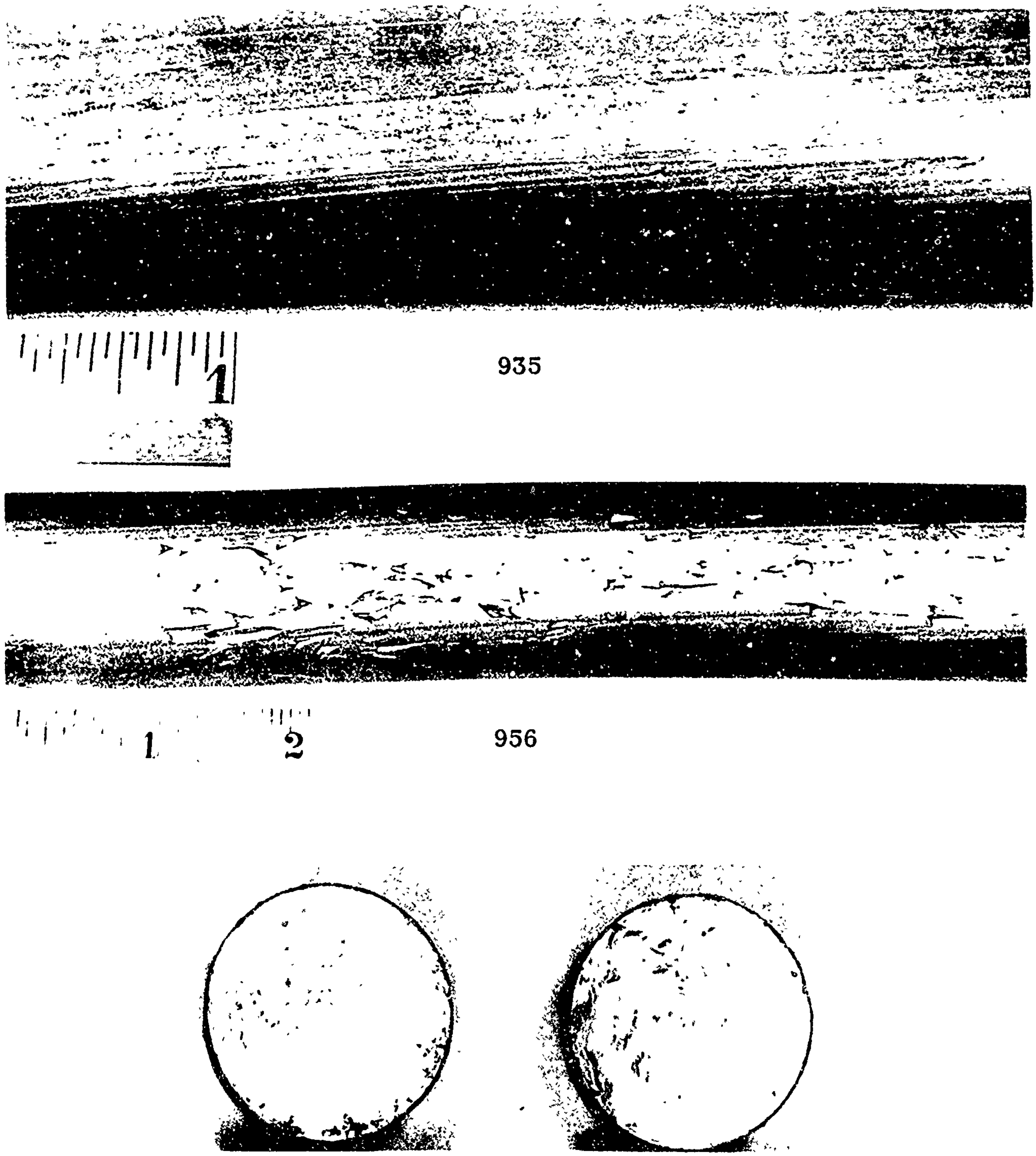


Figure 14 - Closeup of Extrusion Surfaces. Depth of Defects is Indicated in Bottom Photo.

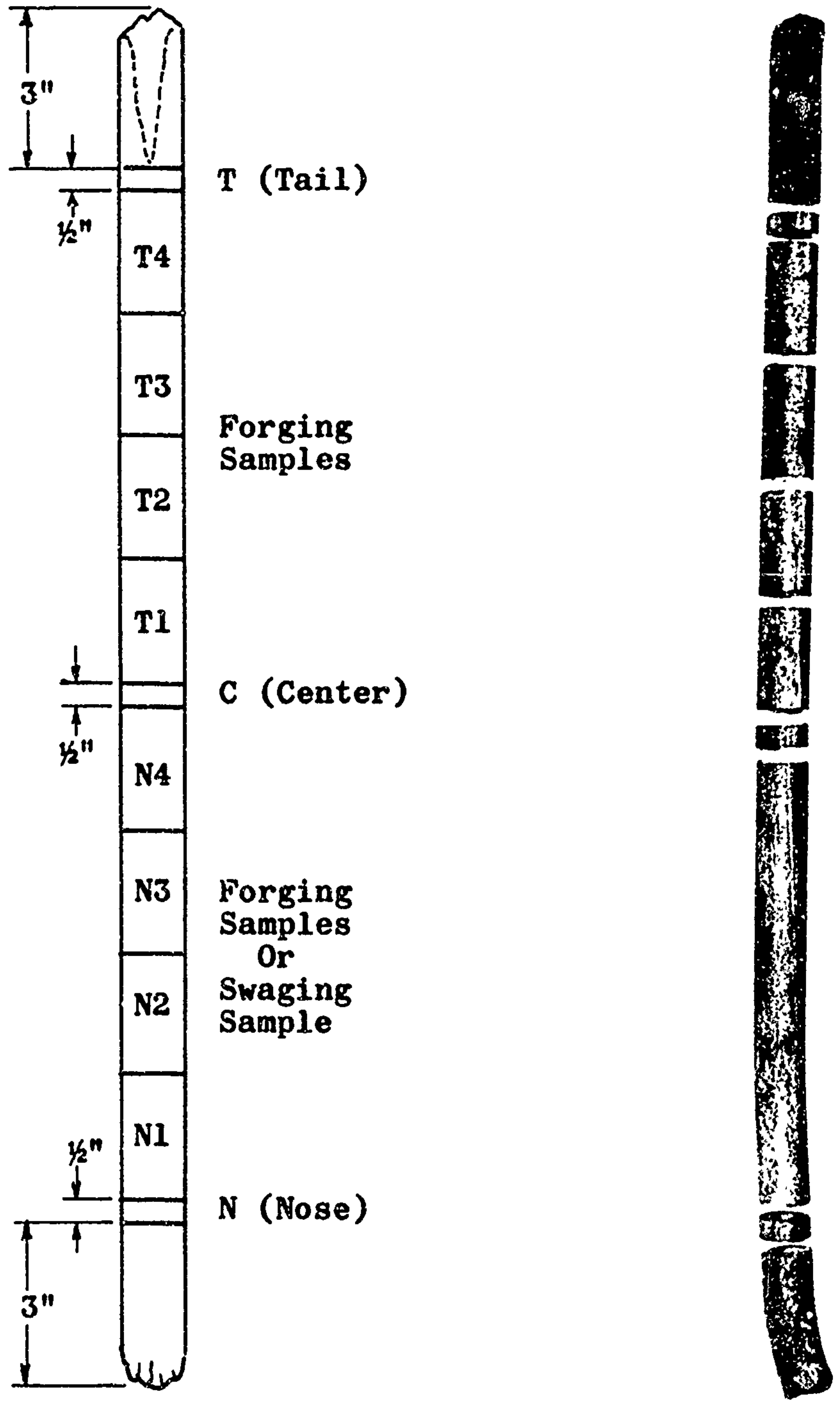
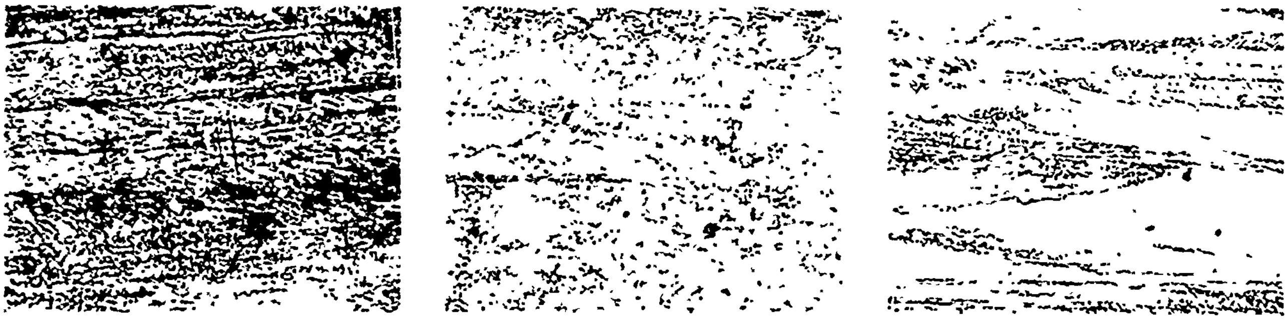


Figure 15 - Extrusion Sample Identification Diagram

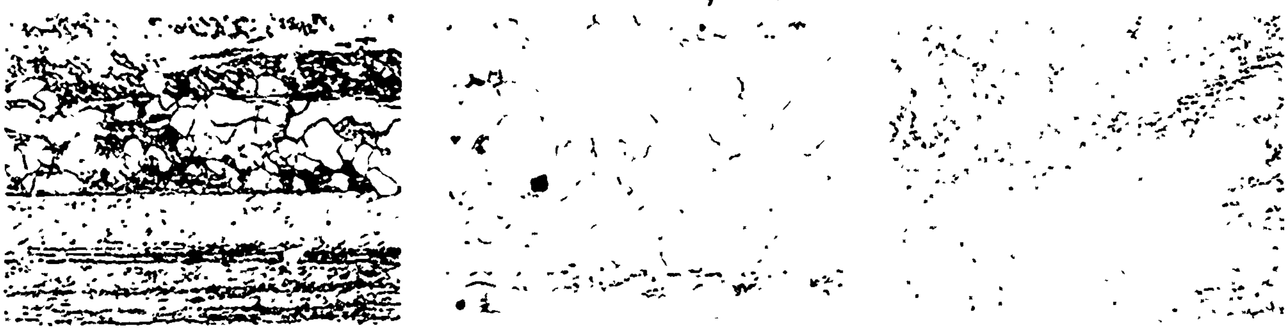


Nose | Center | Tail

Extrusion 738, Universal Cyclops

Nose | Center | Tail

Extrusion 935, AFML



Nose | Center | Tail

Extrusion 995, Wah Chang

Nose | Center | Tail

Extrusion 997, Oremet

Figure 16 - W+0.6Cb Extrusion Structures from Billets Produced by Four Suppliers, Extruded at 3800°F at Approx. 6.5:1.

Electropolished - Murakami's Etch - 50X

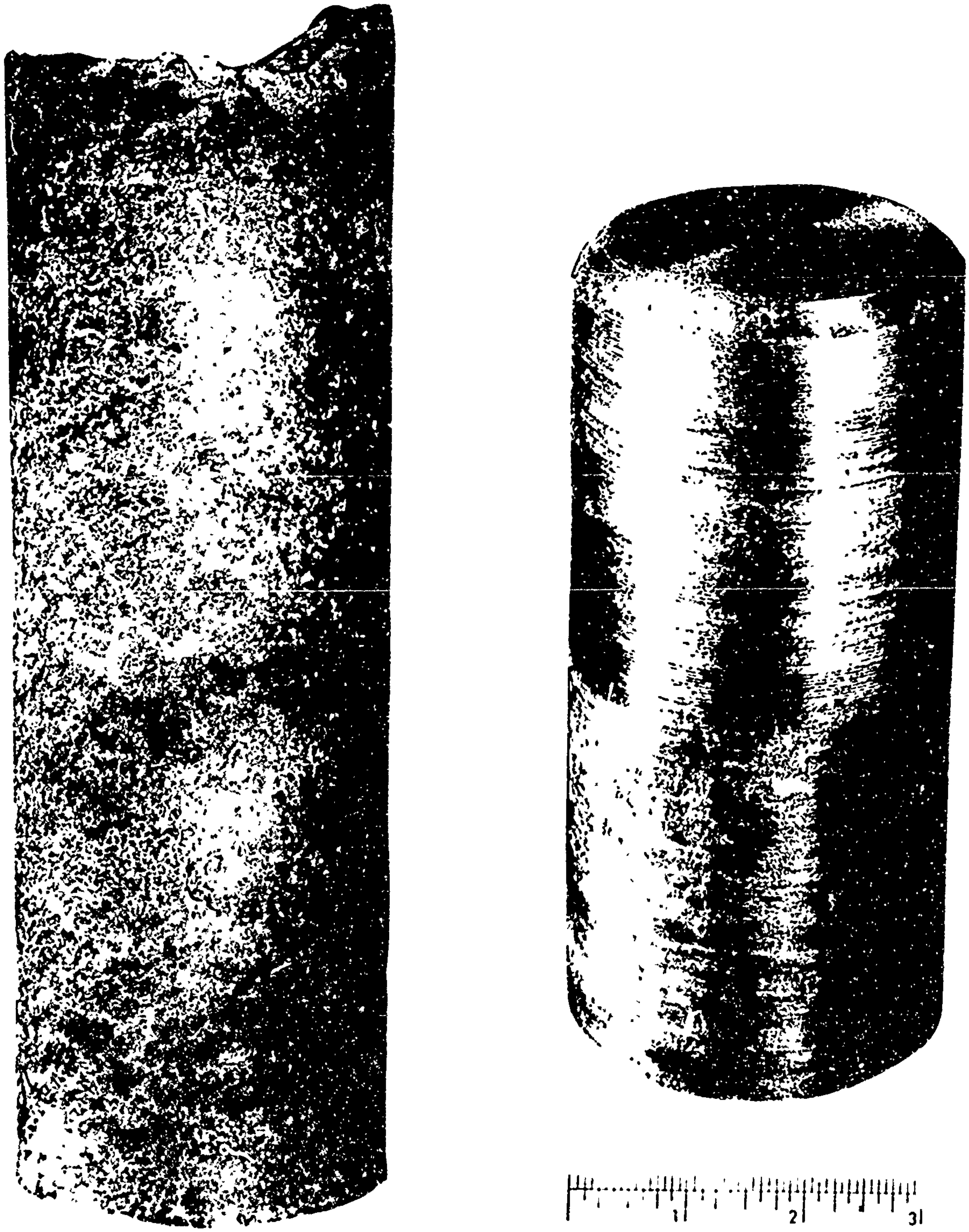


Figure 17 - Arc Cast Ingot and Machined Billet of 92-6-2 Alloy.

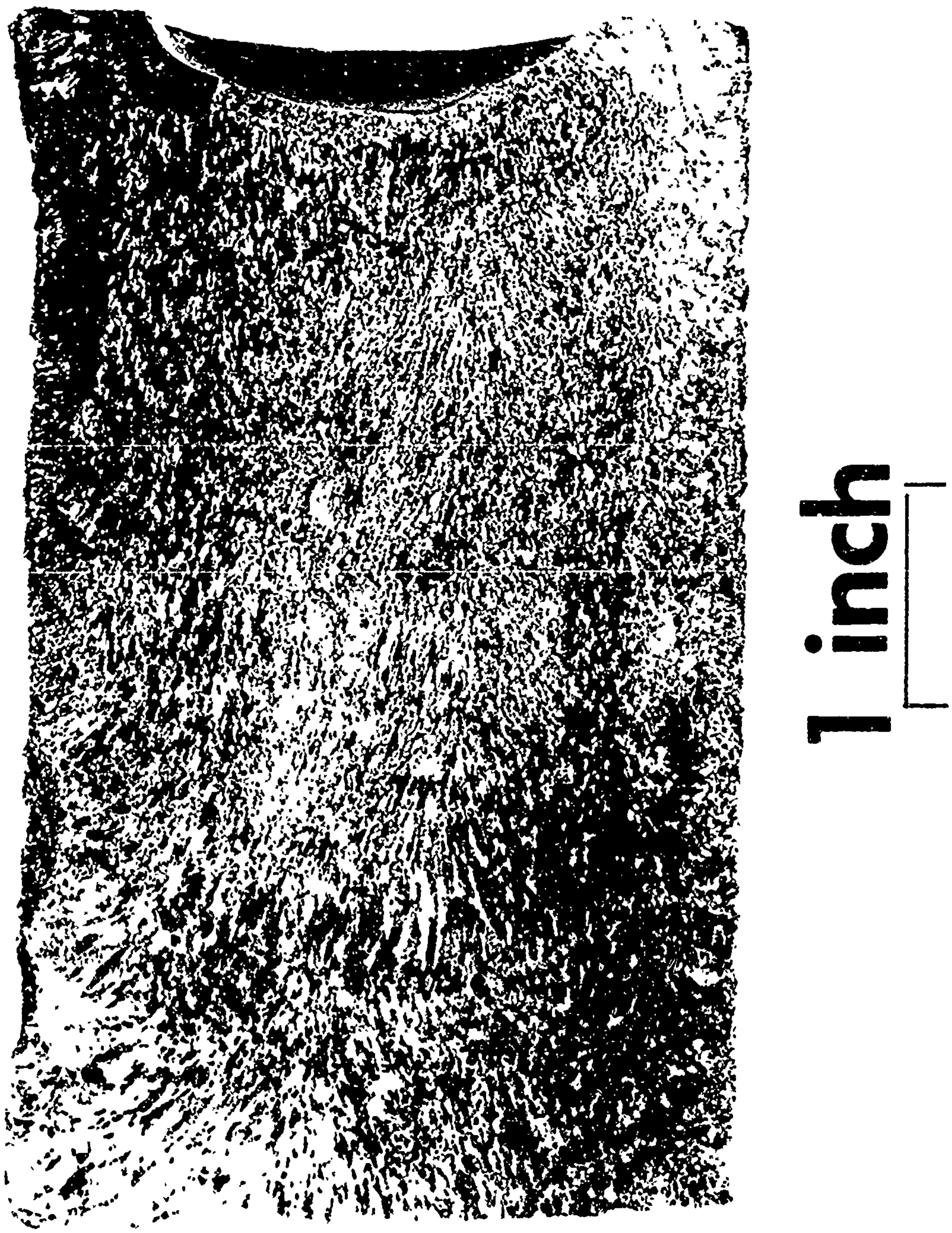


Figure 18 - Macrostructure of 92-6-2 Ingot

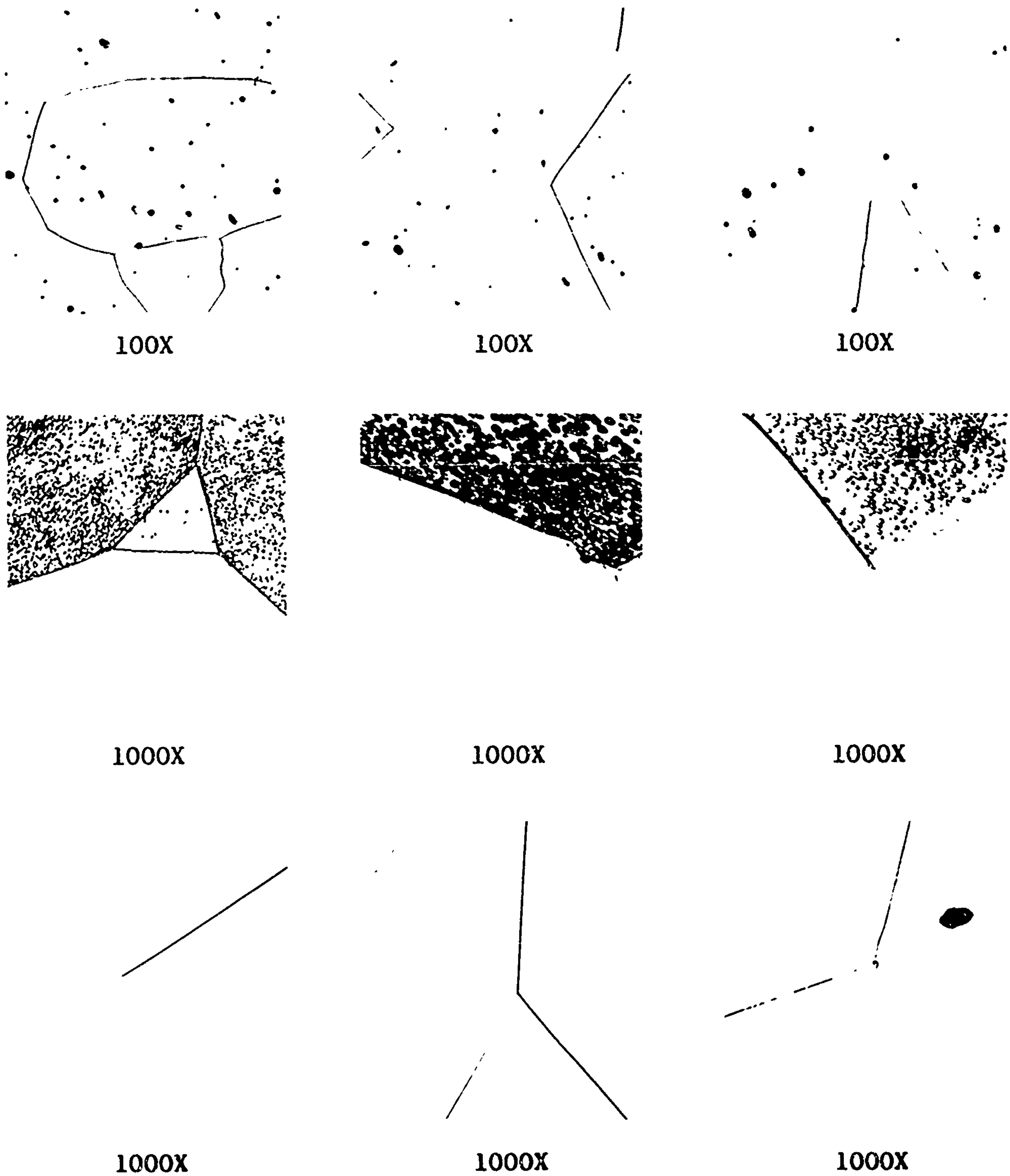


Figure 19 - Microstructure of Vacuum Arc Cast 92-6-2 Ingot VA-69

Electropolished - Murakami's Etch

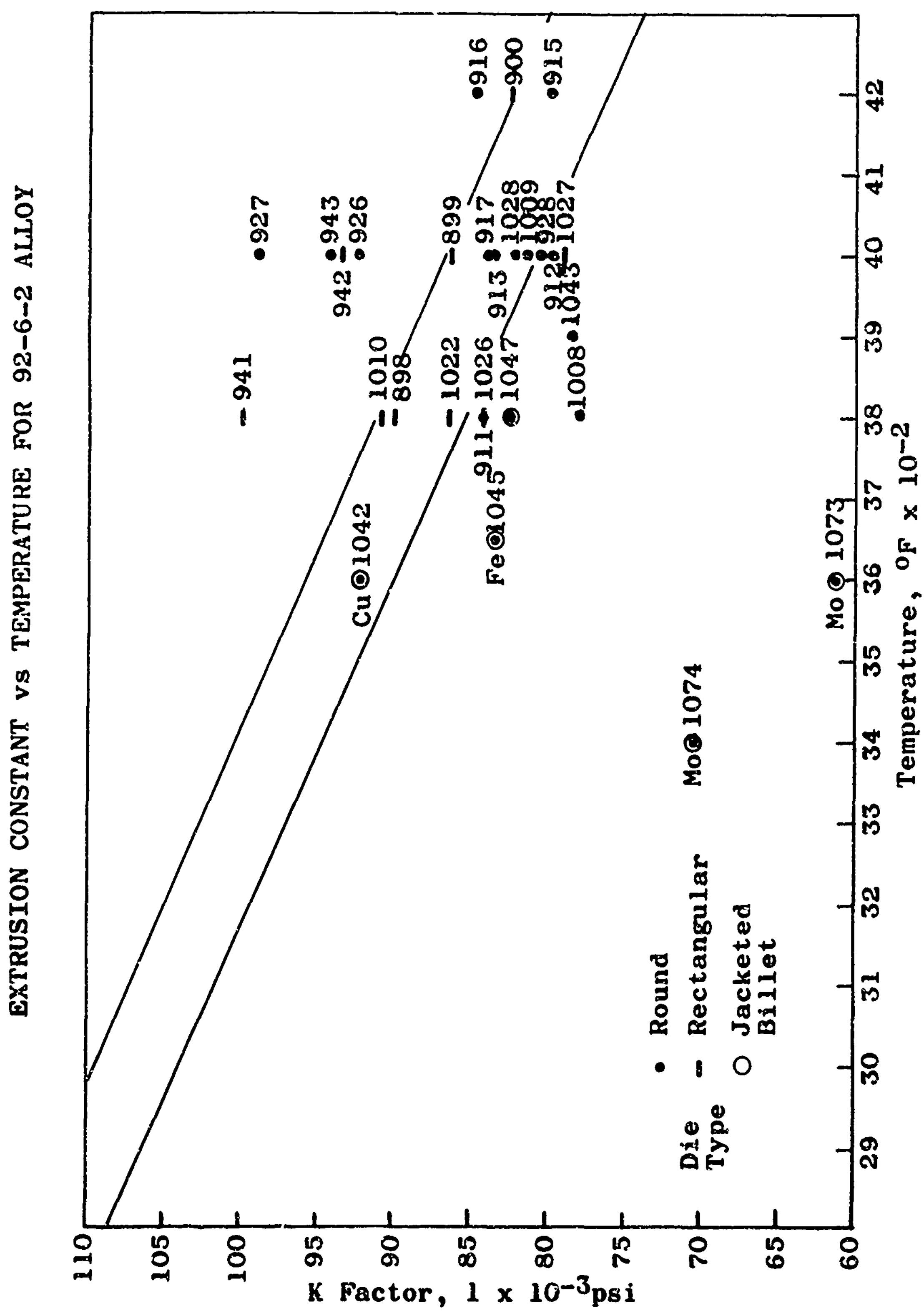


Figure 20 - Relation of Temperature and Extrusion Constant for 92-6-2 Alloy.

928 927 926

Figure 21 - Examples of Poor Extrusion Surfaces of 92-6-2 Alloy Melted in 3½-Inch Mold.

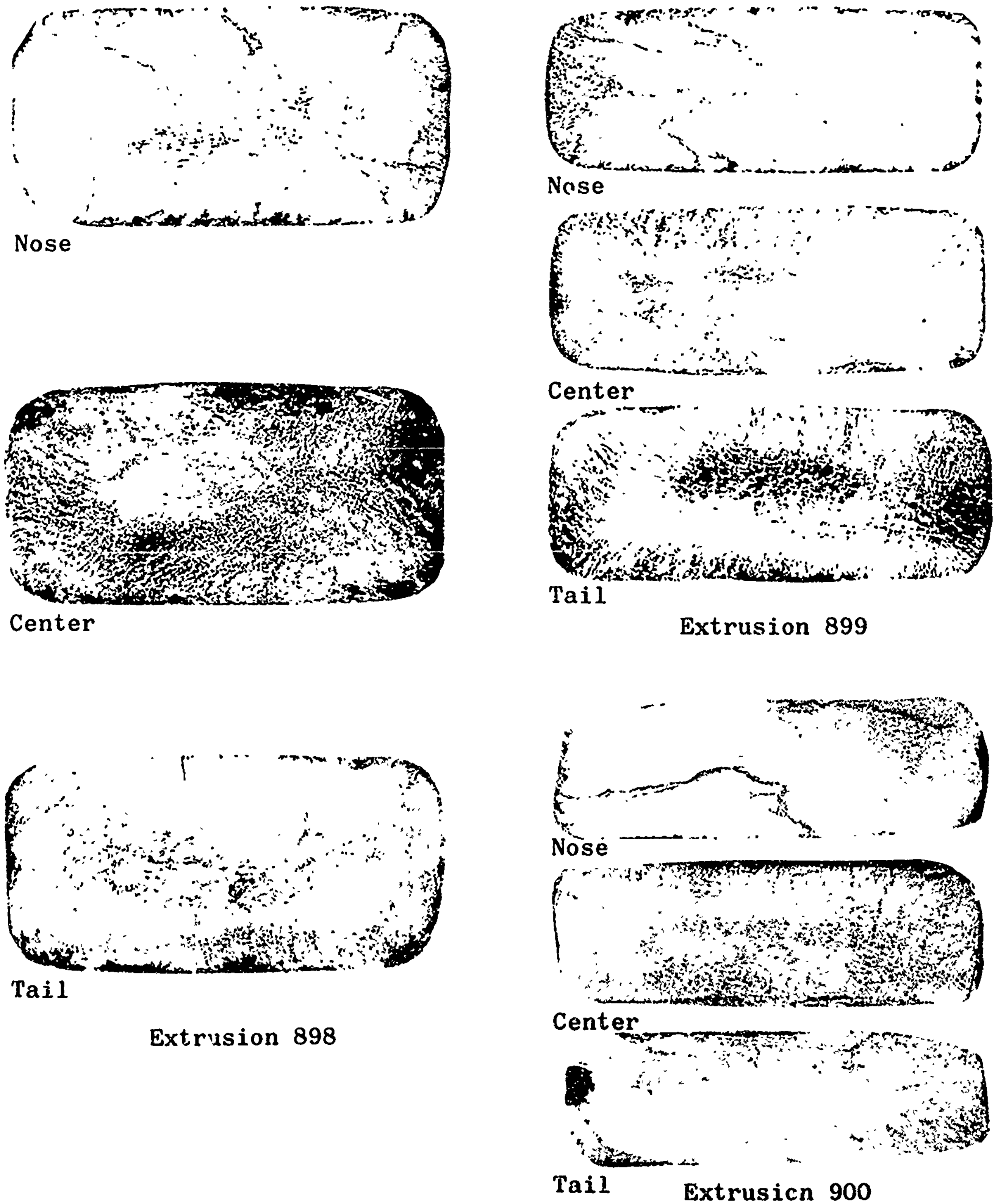
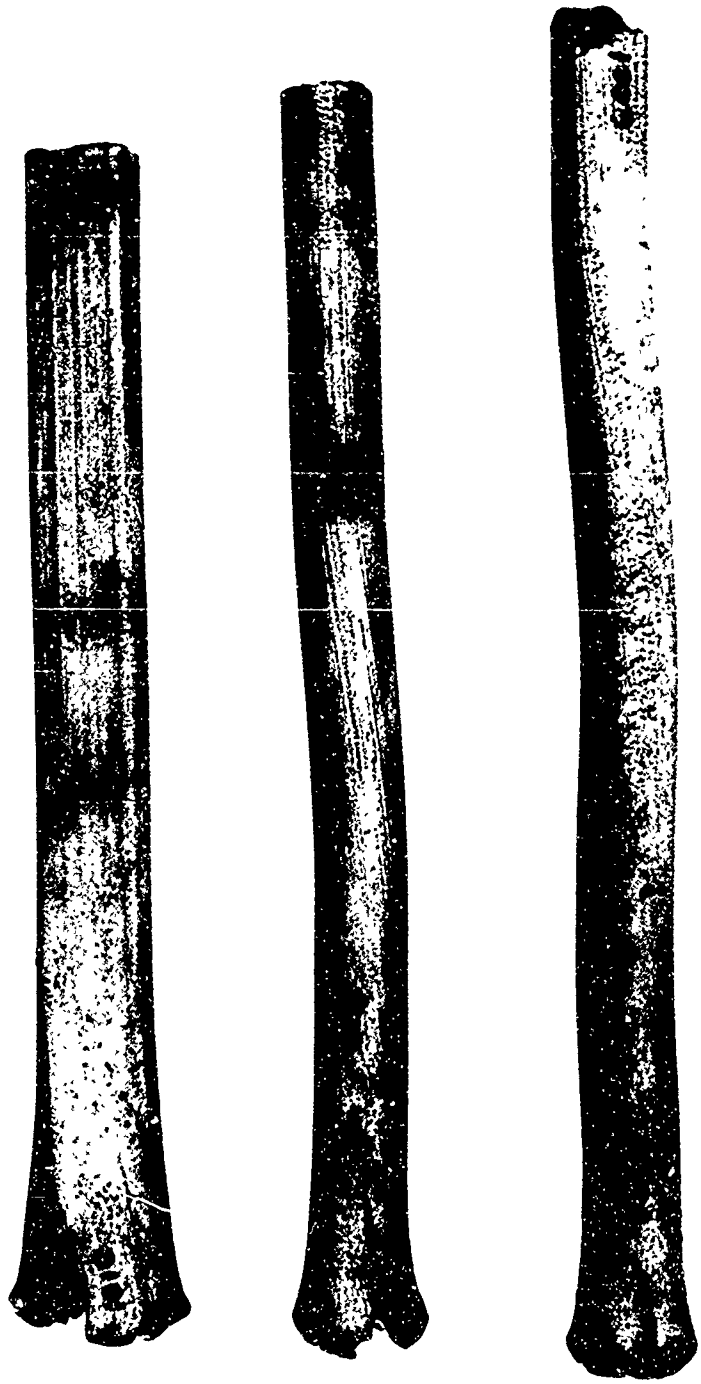
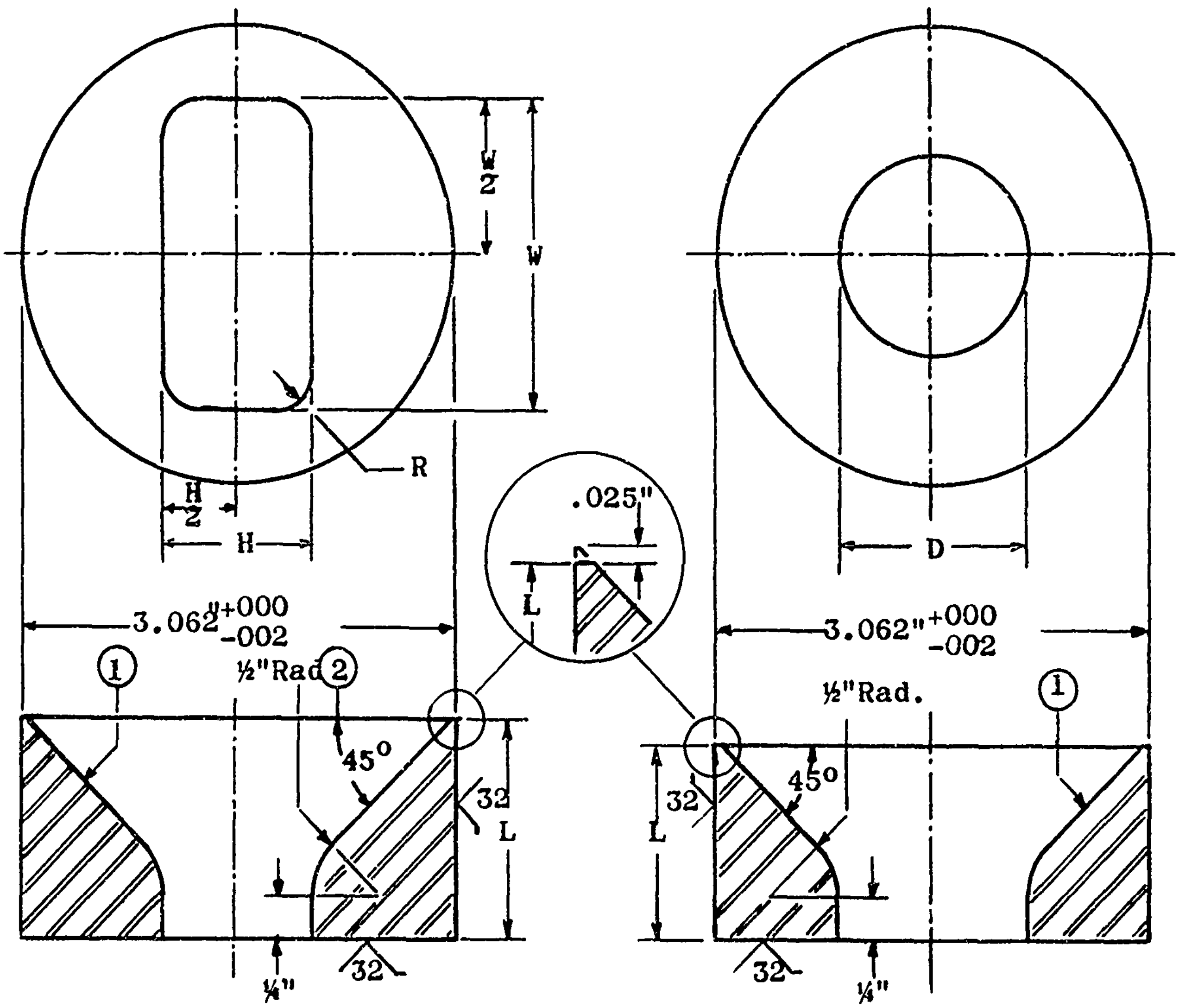


Figure 22 - Examples of Internal Cracks in 92-6-2 Extrusions
(Approx. 1½X)



1010 1009 1008

Figure 23 - Examples of Fair Extrusion Surfaces of 92-6-2 Alloy Melted in 4-inch Mold.

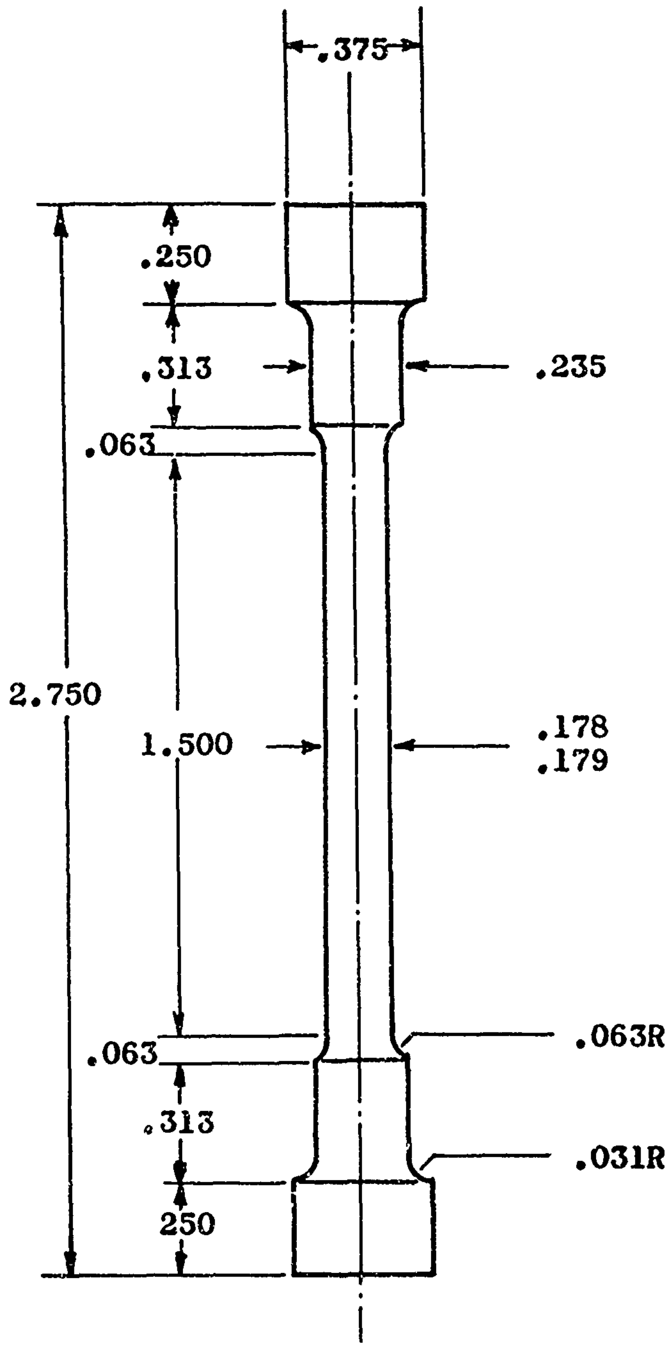


W	H	L	R	Ratio
2.050	1.020	1.452	¼	4:1
2.050	0.825	1.549	¼	5:1
2.050	0.705	1.609	¼	6:1
2.050	0.688	1.628	¼	7:1
2.050	0.552	1.686	¼	8:1
2.050	0.355	1.784	11/64	10:1

D	L	Ratio
1.825	1.049	3:1
1.590	1.167	4:1
1.428	1.248	5:1
1.310	1.307	6:1
1.218	1.353	7:1
1.143	1.390	8:1
1.082	1.421	9:1
1.028	1.448	10:1

1. Rough Finish required on this surface.
2. Angle will hold only at centerline of sides "W". Remainder of entrance cone to taper smoothly into ½" entrance radius.
3. Break all sharp corners.
4. Material - SAE H-12 tool steel, H.T. Rc 40-44.
5. Application of 30-mil ZrO_2 coating produces indicated ratios.

Figure 24 - Detail of Rectangular and Round Extrusion Dies



dimensions are in inches

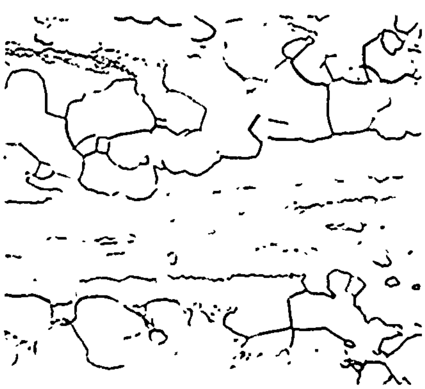
Figure 25 - Specimen for 3000°F Tensile Tests

913N

913C

915C

915T

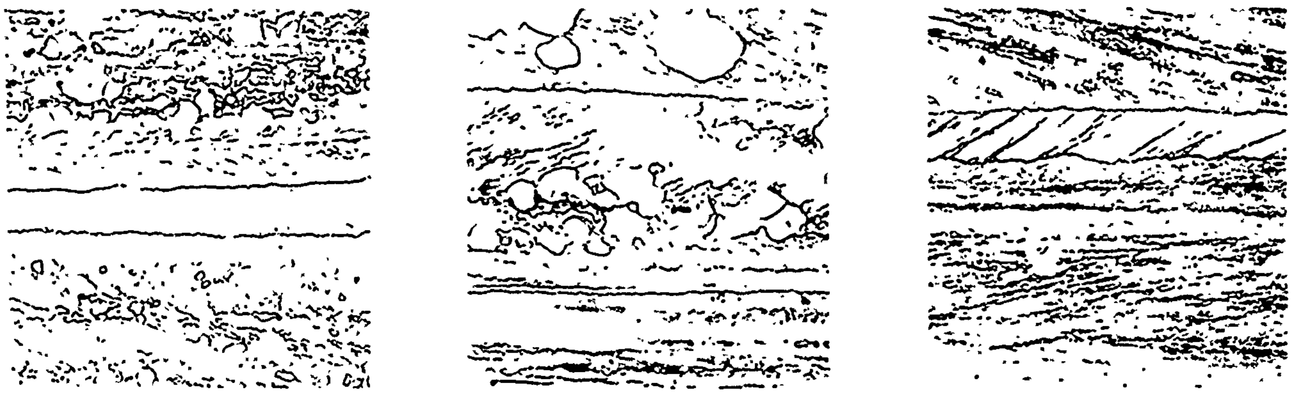


928C

928T

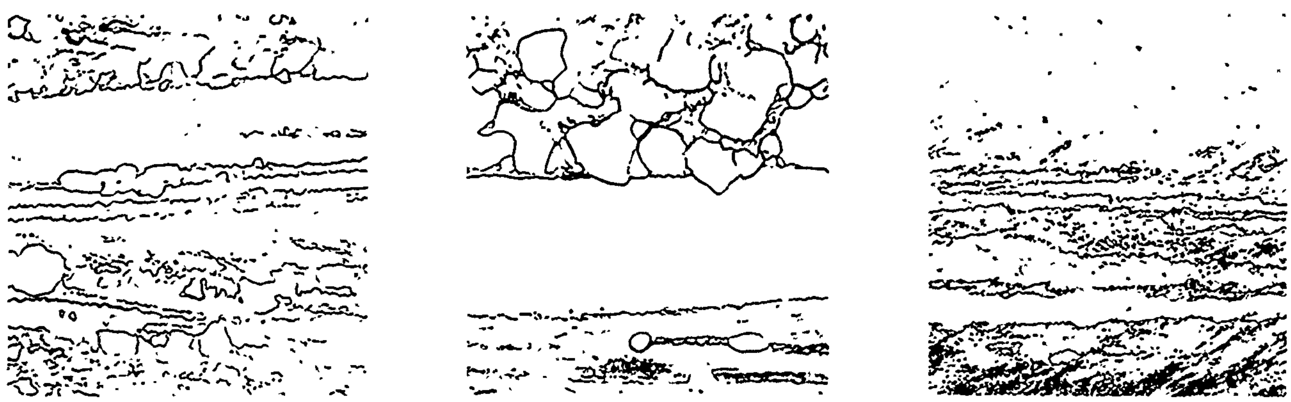
Figure 26 - Microstructures of 92-6-2 Samples from which Tensile Samples were Machined.

Electropolished - Murakami's Etch - 250X



Nose Center Tail

Extrusion 898, 3800°F, 4.4:1



Nose Center Tail

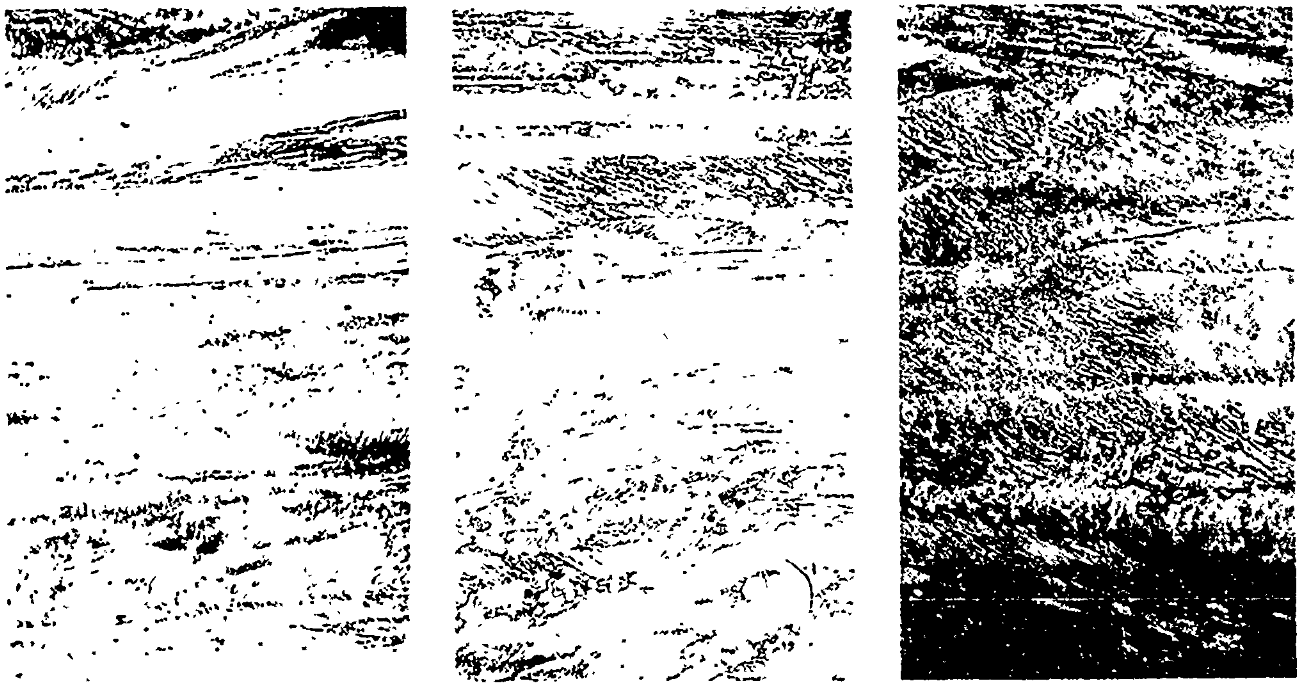
Extrusion 899, 4000°F, 5.8:1

Nose Center Tail

Extrusion 900, 4200°F, 7.4:1

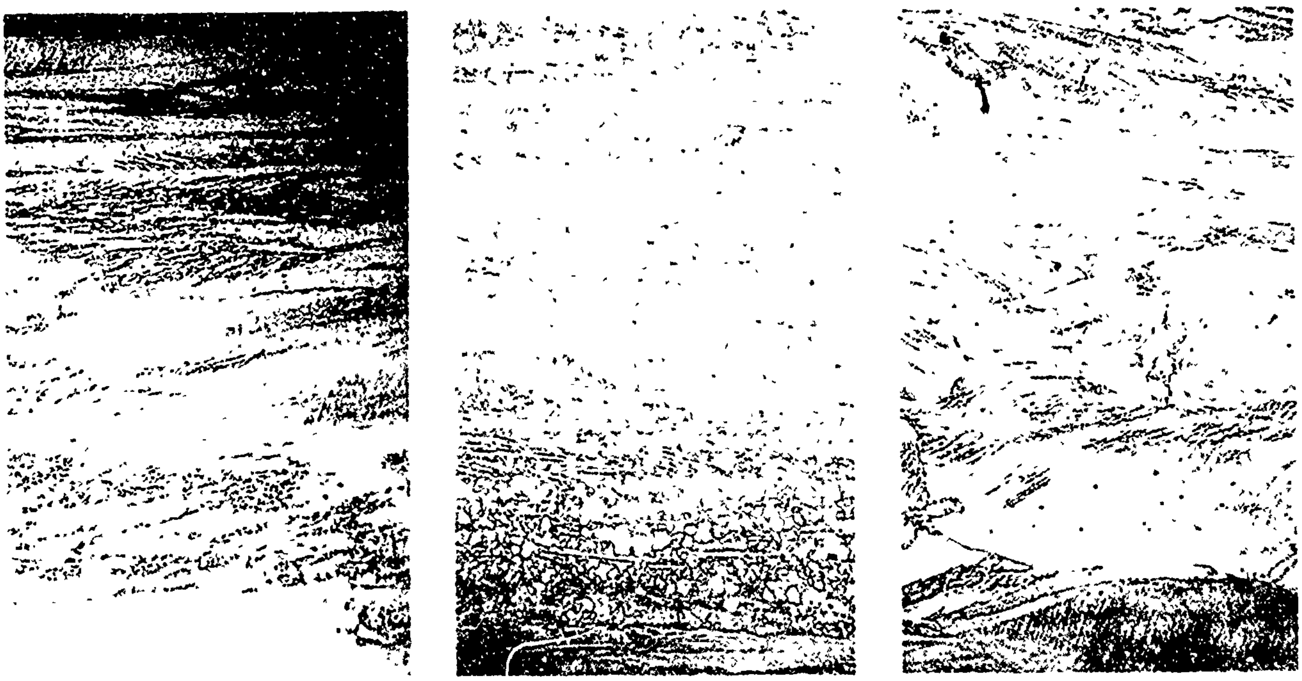
Figure 27 - Microstructures of 92-6-2 Extrusions

Electropolished - Murakami's Etch - 250X



Nose Center Tail

Extrusion 943, 4000°F, 4.3:1



Nose Center Tail

Extrusion 1028, 4000°F, 7.3:1

Figure 28 - Microstructures of 92-6-2 Extrusions Showing Banding.

Electropolished - Murakami's Etch - 50X

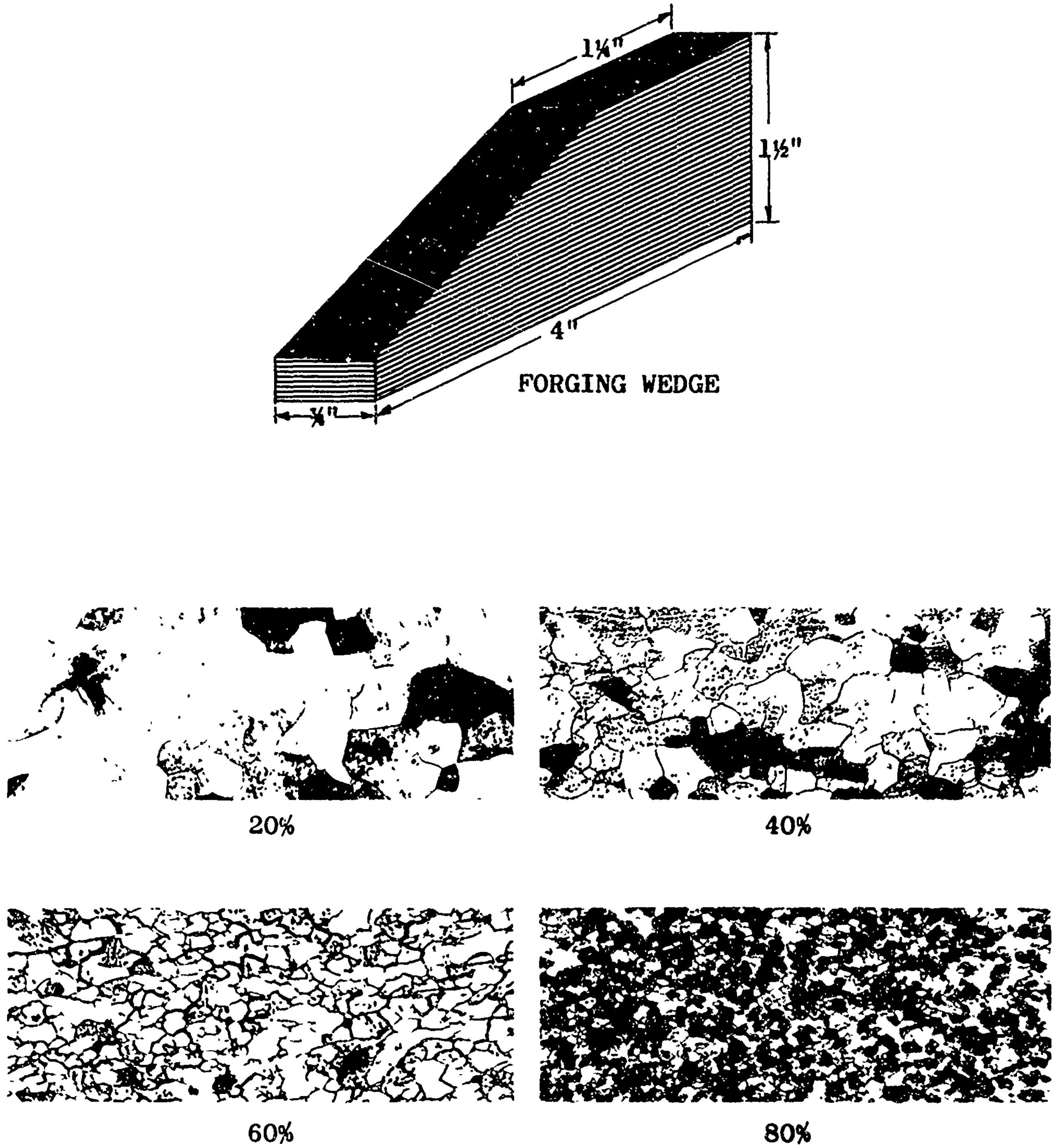
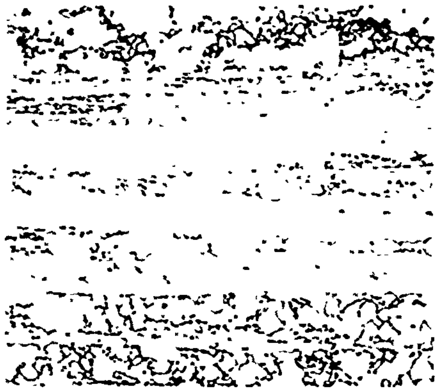


Figure 29 - Effect of Percent Reduction on Recrystallized Grain Size of Forged W+0.6Cb Alloy. Wedge from Extrusion 993 was Annealed at 3400°F for 1 Hour, Forged at 2800°F, and then Annealed at 3000°F for 1 Hour.

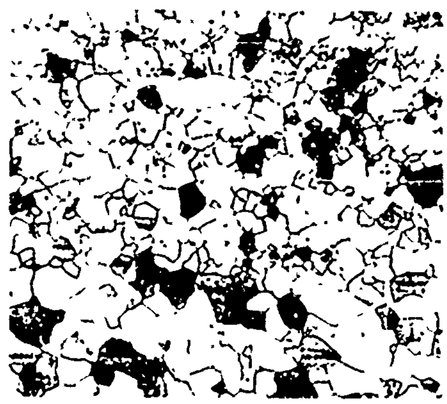
Electropolished - Murakami's Etch - 50X



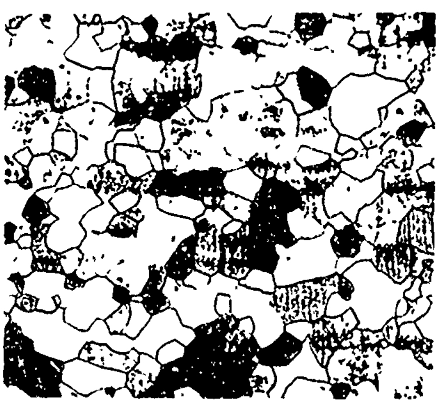
2600°F

2800°F

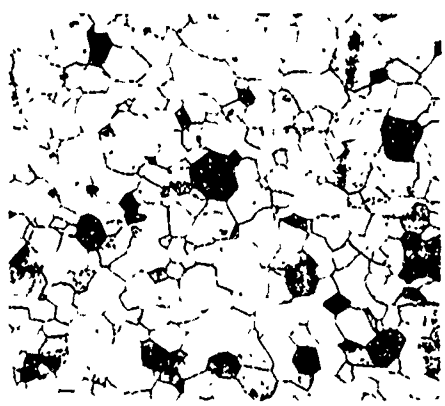
3000°F



3200°F



3400°F



3600°F

Figure 30 - Recrystallization Behavior of Extruded 92-6-2 Alloy when Subjected to Annealing for 1 Hour at the Indicated Temperatures. Samples from Extrusion 899.

Electropolished - Murakami's Etch - 250X

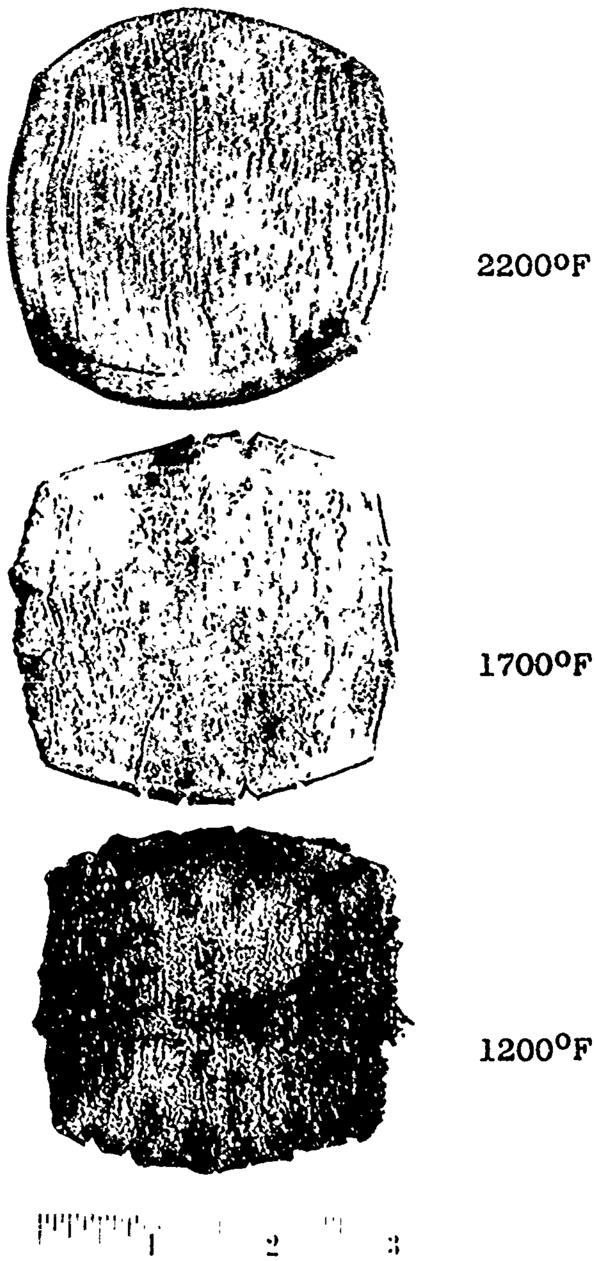
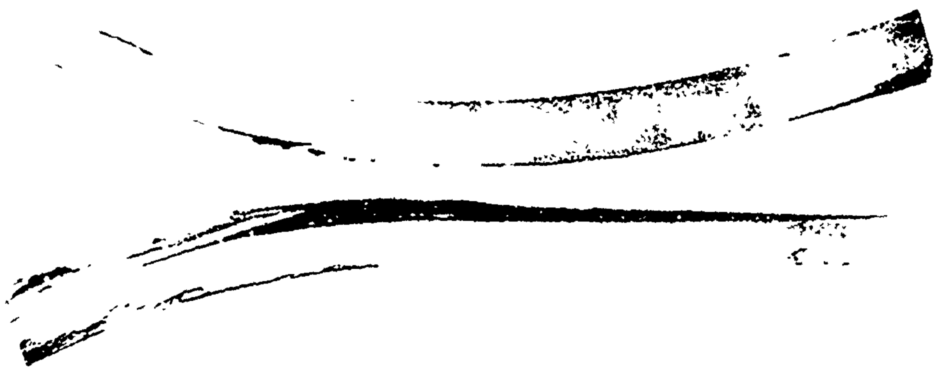


Figure 31 - Samples of 92-6-2 Alloy Forged 70 Percent at Indicated Temperatures.

759 (Extruded and Recrystallized)



763 (Extruded, Forged, and Recrystallized)

992 (Extruded, Forged, and Recrystallized)

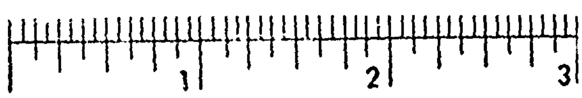


Figure 32 - W+0.6Cb Sample Failures Encountered During Early Rolling Stages.

974, Annealed, Swaged 58%

Swaged from 1.22" to .940" (41%) @ 2700°F

Annealed 1 hour @ 3400°F

Swaged from .940" to .610" (58%) @ 2700°F

994, Annealed, Swaged 35%

Swaged from 1.13" to .840" (45%) @ 2400°F

Annealed 1 hour @ 3200°F

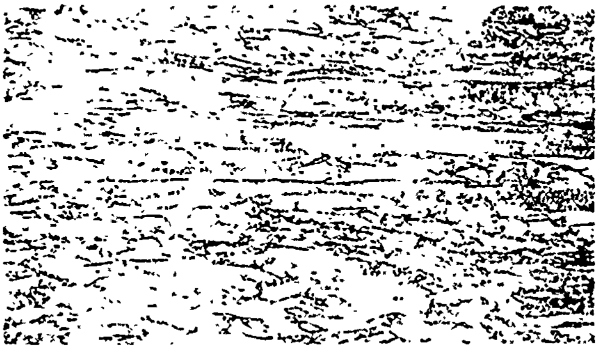
Swaged from .840" to .687" (35%) @ 2200°F.

995, Annealed, Swaged 58%

Swaged from 1.19" to .940" (39%) @ 2700°F

Annealed 1 hour @ 3200°F

Swaged from .940" to .610" (58%) @ 2400°F



997, Annealed, Swaged 58%

Swaged from 1.20" to .940" (39%) @ 2700°F

Annealed 1 hour @ 3200°F

Swaged from .940" to .610" (58%) @ 2700°F

SAMPLE HISTORIES

Figure 33 - Annealed and Swaged W+0.6Cb Microstructures. Tensile Results are shown in Table 17, and Extrusion Structures of 994, 995, and 997 are shown in Figures 10 and 16.

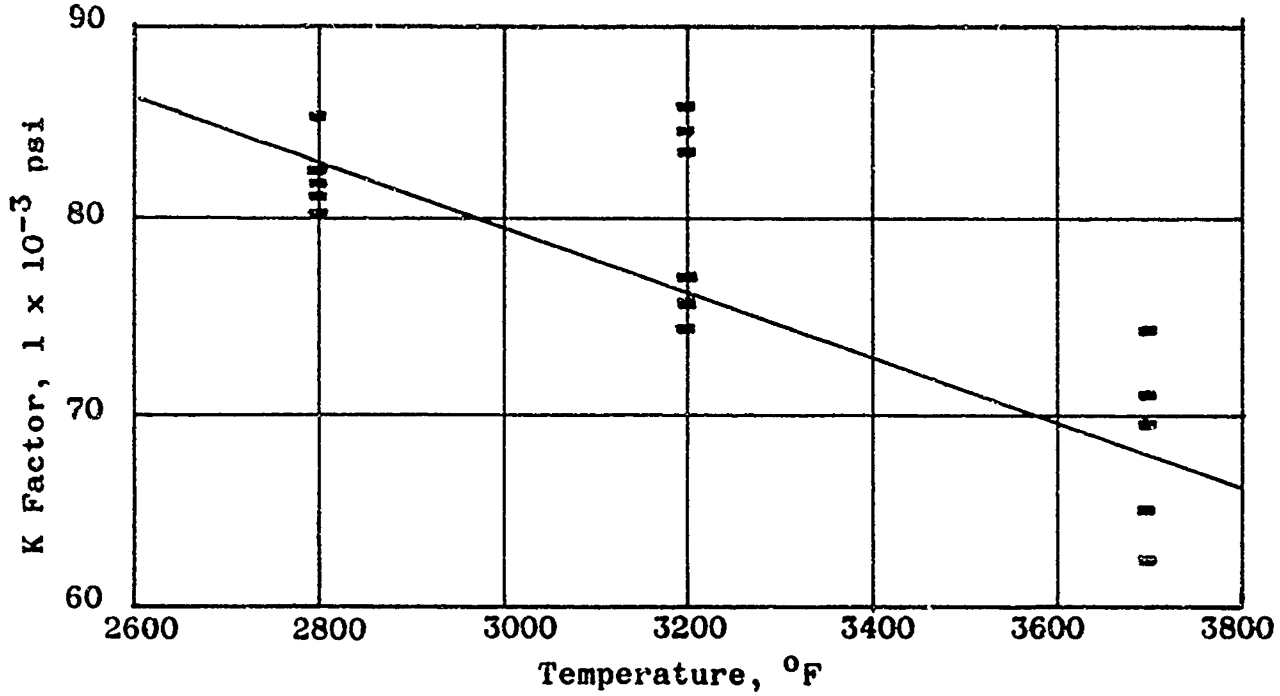
Electropolished - Murakami's Etch - 50X

Extrusion 1028, Swaged to .937"

Extrusion 1043, Swaged to .937"

Figure 34 - Extruded and Swaged 92-6-2 Microstructures.

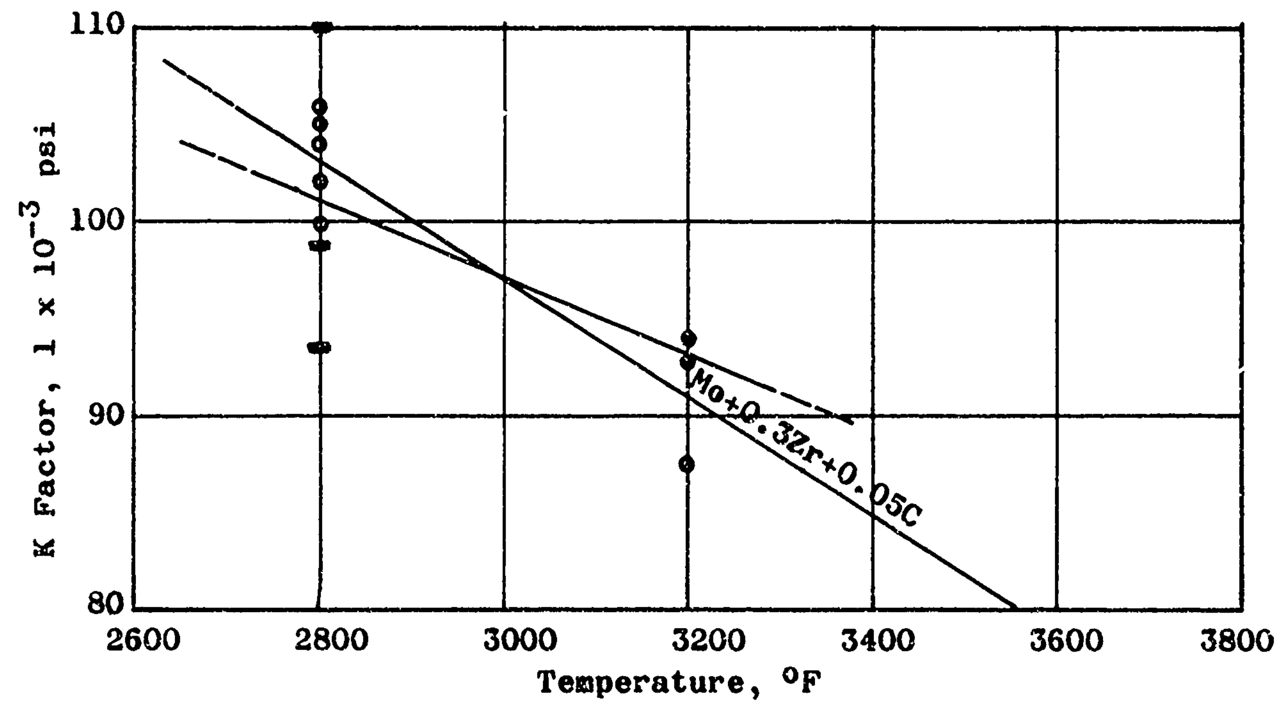
Electropolished - Murakami's Etch - 50X



Mo+0.5Ti+0.1Zr+0.02C

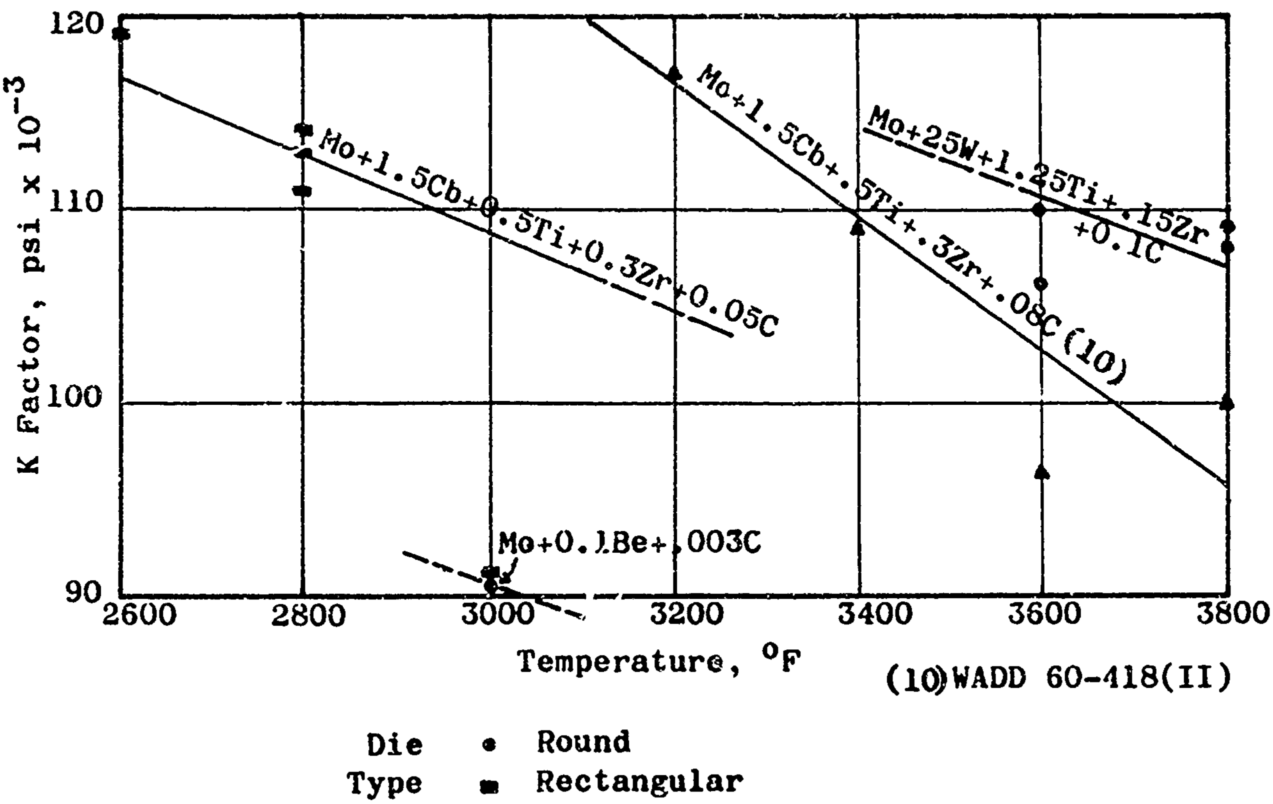
Die • Round

Type ▬ Rectangular



Mo+1.25Ti+0.3Zr+0.10C and Mo+0.3Zr+0.05C

Figure 35 - Relation of Temperature and Extrusion Constant for Molybdenum-Titanium-Zirconium Alloys.



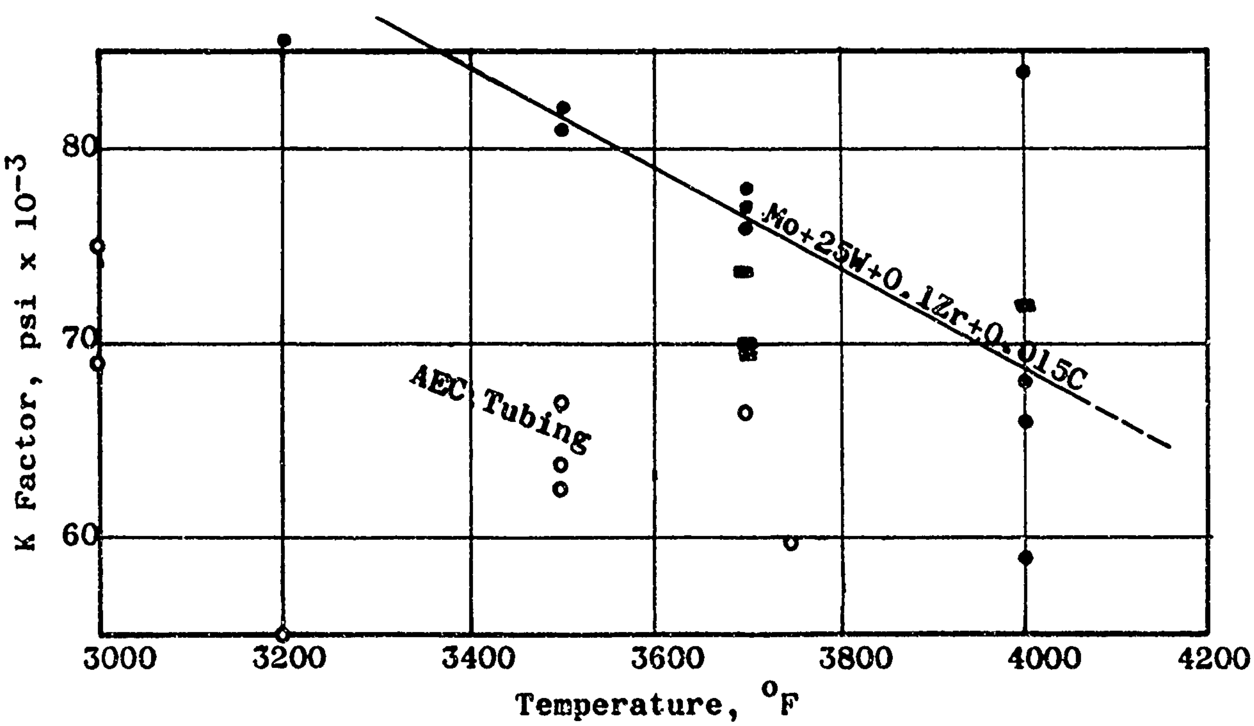


Figure 36 - Relation of Temperature and Extrusion Constant for Molybdenum-Columbium and Molybdenum-Tungsten Alloys, and Molybdenum Tubing.

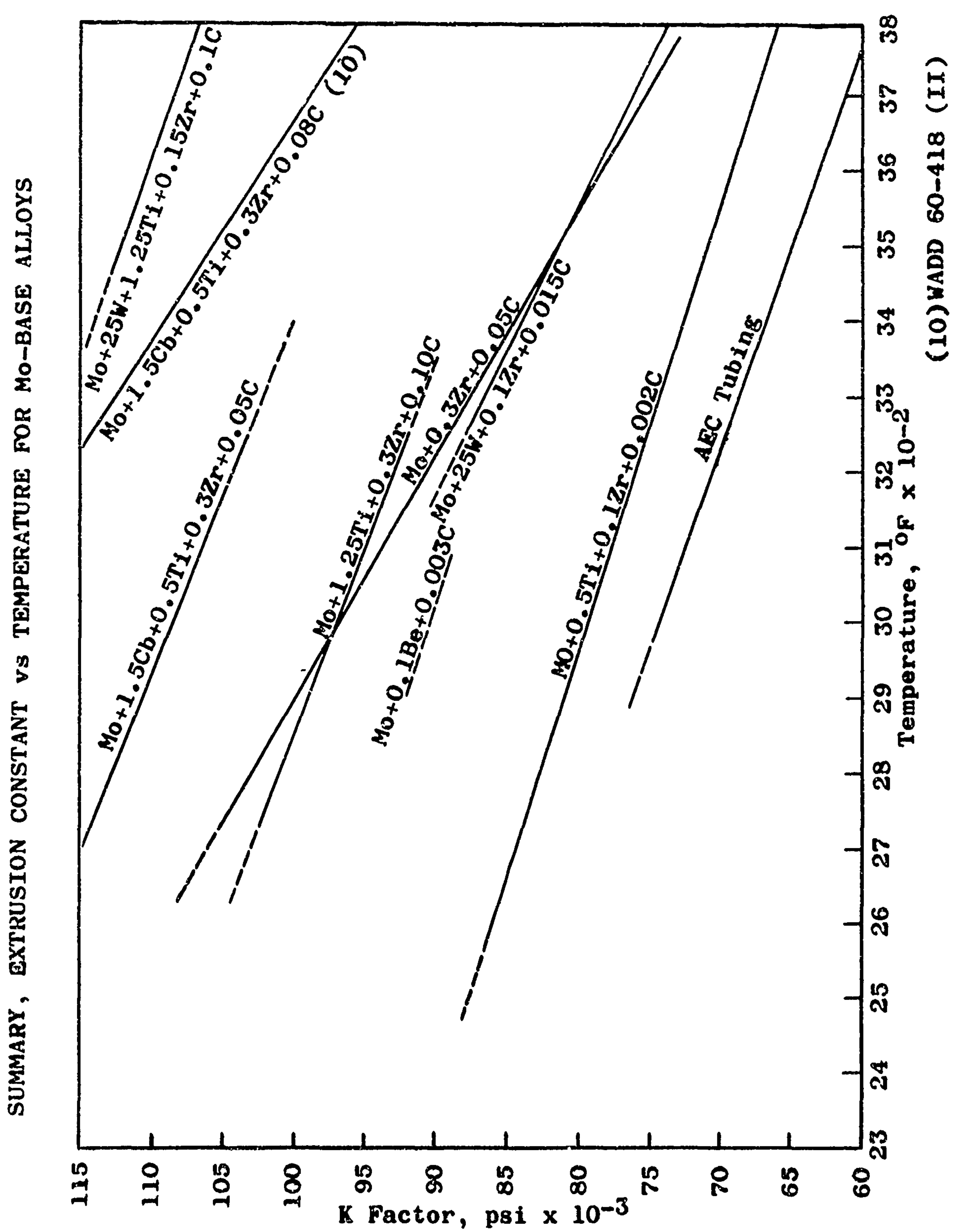


Figure 37 - Relation of Temperature and Extrusion Constant for Mo-Base Alloys (Summary).

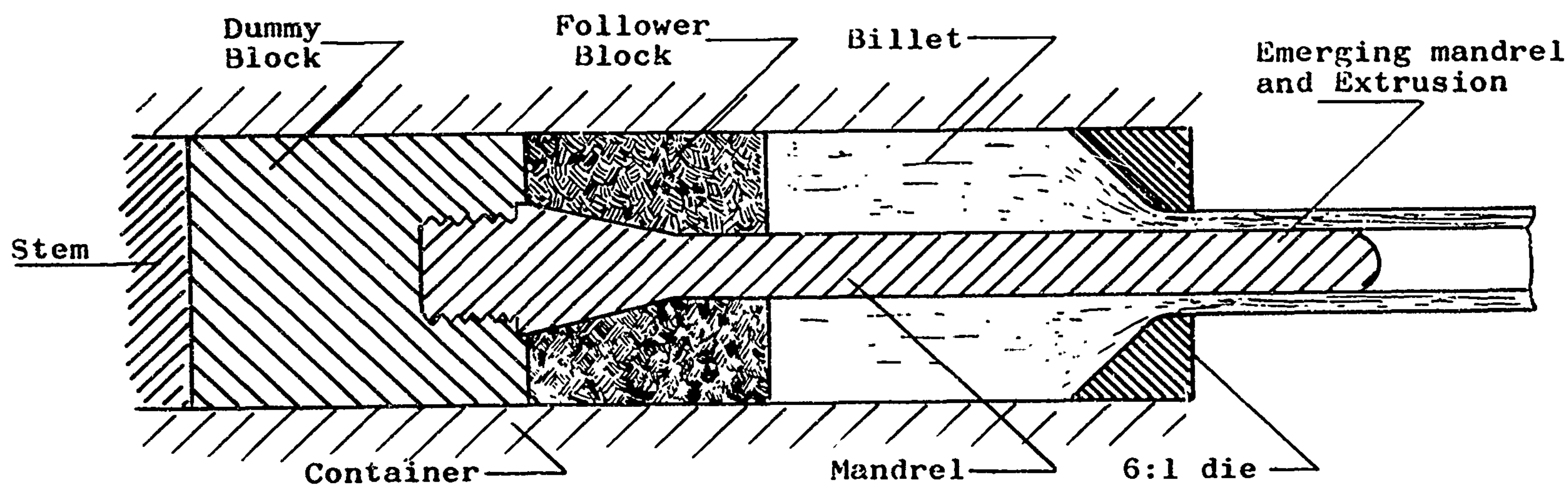


Figure 38 - Sketch of Dummy Block and Mandrel Arrangement Used to Extrude Molybdenum Tubing.

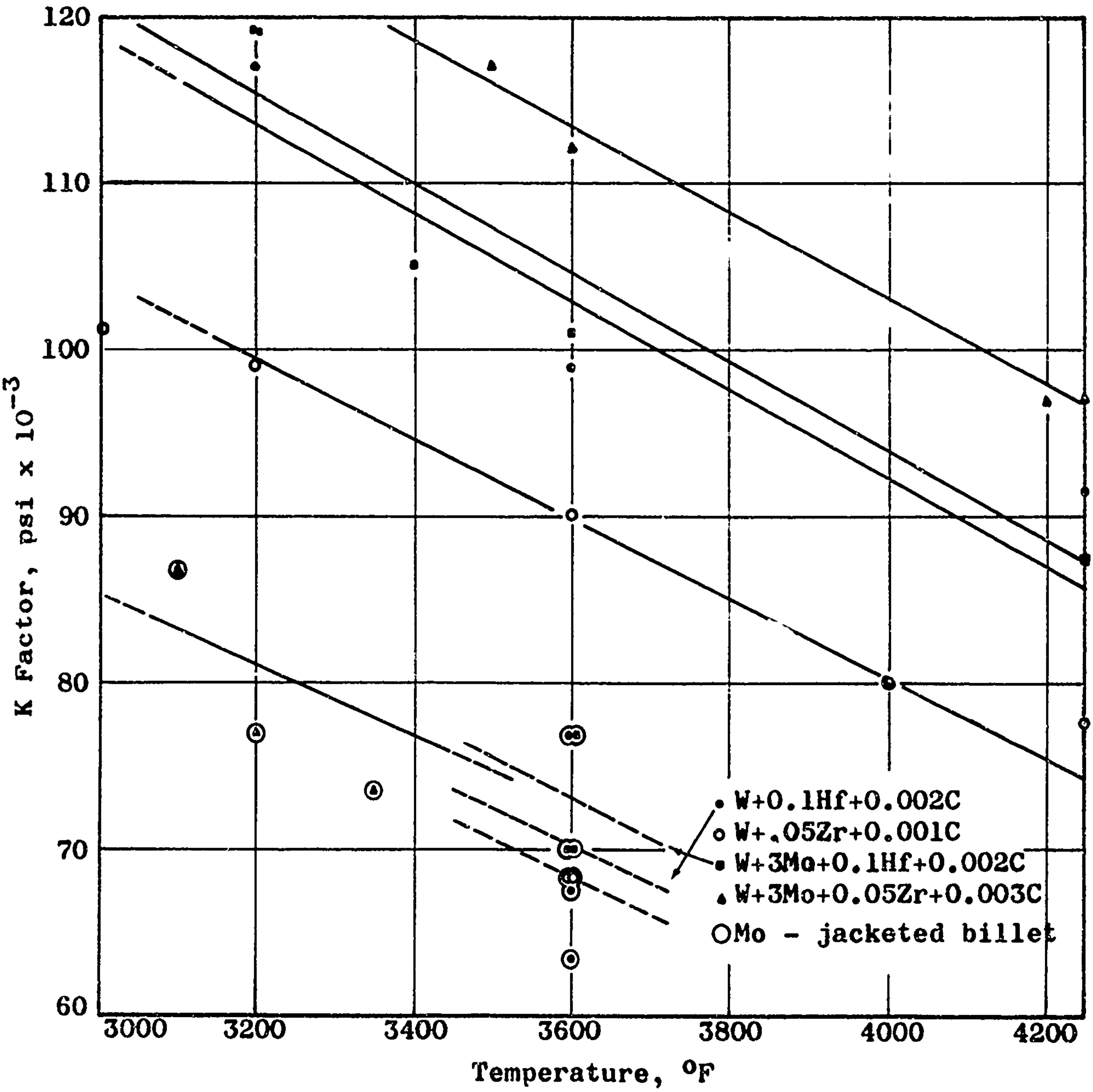
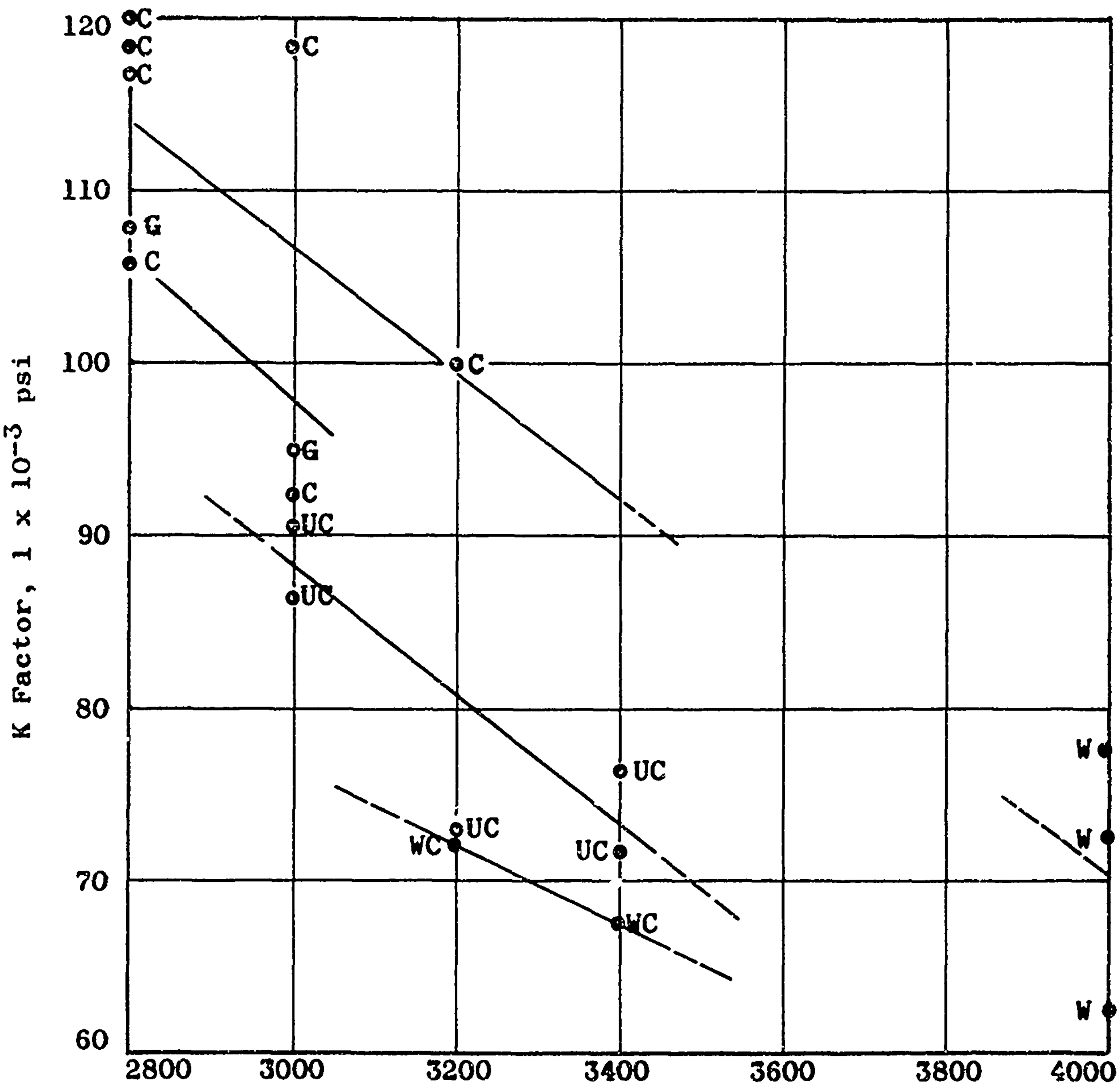


Figure 39 - Relation of Temperature and Extrusion Constant for High-Strength Tungsten-Base Alloy Billets Produced by Climax Molybdenum Co.



Temperature, °F

o WADD 60-418 (II)(10)

C - Climax Molybdenum Co. (Arc Cast)
G - General Electric (Sintered)
UC - Universal Cyclops (Arc Cast)
W - Westinghouse (Sintered)
WC - Wah Chang (Sintered)

Figure 40 - Relation of Temperature and Extrusion Constant for Unalloyed Tungsten from Several Suppliers.

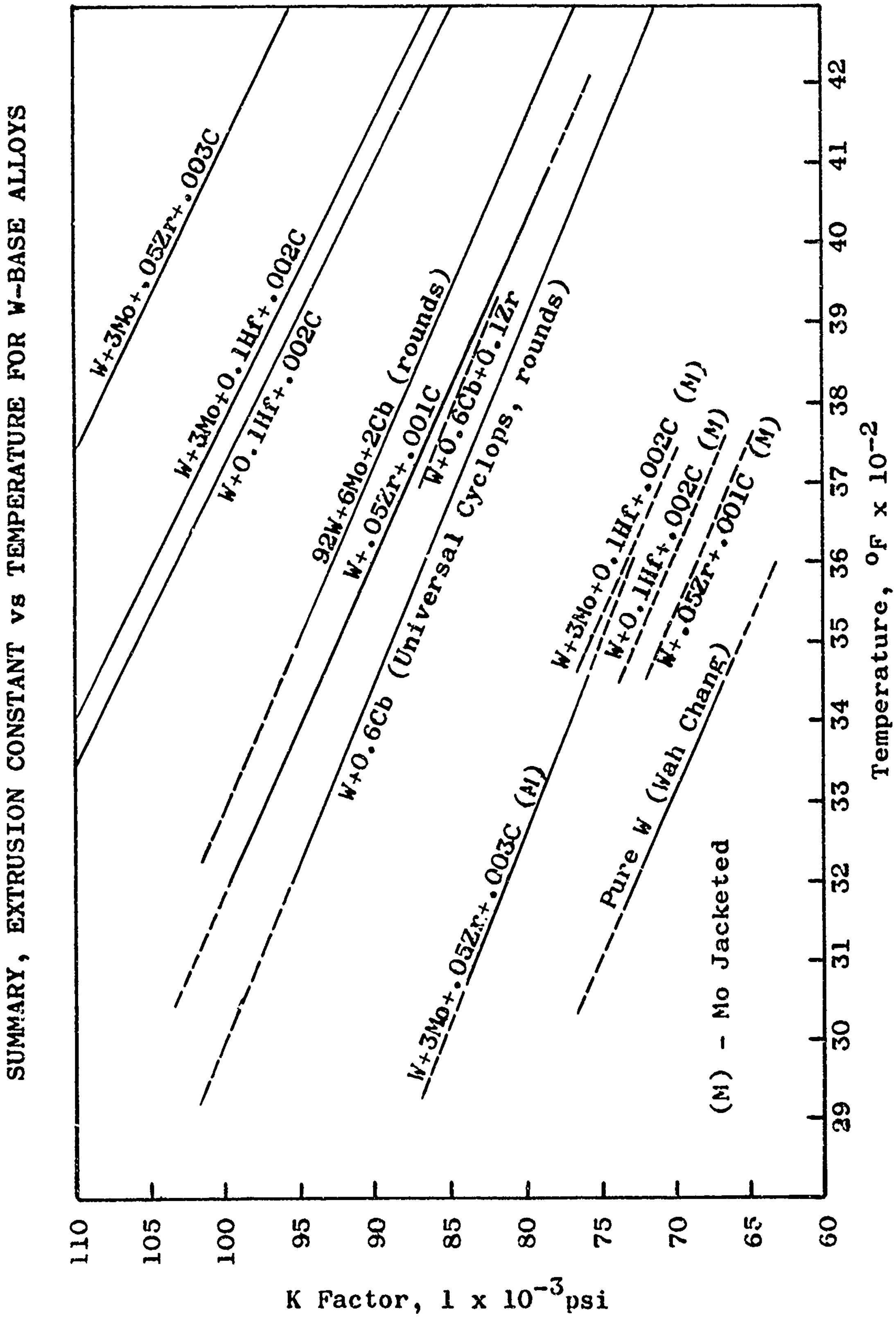


Figure 41 - Relation of Temperature and Extrusion Constant for W-Base Alloys (Summary).